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THESIS

AN ASSESMENT OF EMERGING WIRELESS BROADBAND TECHNOLOFIES

by

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December 2001

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AN ASSESSMENT OF EMERGING WIRELESS BROADBAND TECHNOLOGIES

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LIST OF ABBREVIATIONS

ABR	Available Bit Rate
ATM	Asynchronous Transfer Mode
APD	Advance Photo Diode
bps	Bits per Second
BPSK	Binary Phase Shift Key
CBR	Constant Bit Rate
CO	Central Office
CPE	Customer Premices Equipment
CSMA	Code Division Multiple Access
DSL	Digital Subscription Lines
EMS	Element Management Systems
FCC	Federal Communication Commission
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FSO	Free Space Optics
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
GDP	Gross Domestic Product
HALE	High Altitude Long Endurance
HFC	Hybrid Fiber/Coax
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force

IP	Internet Protocol
ISI	Intersymbol Interference
ISP	Internet Service Provider
ITU	International Telecommunication Union
LAN	Local Area Network
LMDS	Local Multipoint Distribution Services
LOS	Line of Sight
MAC	Medium Access Control
MPLS	Multiprotocol Label Switching
MIP	Mesh Insertion Points
NMS	Network Management System
NMU	Network Management Unit
NOC	Network Operation Center
NPS	Naval Postgraduate School
QoS	Quality Of Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Key
PIN	Positive-Intrinsic-Negative
PMP	Point-to-Multipoint
POP	Point-of-Presence
PSDN	Public Switched Telephone Network
PSK	Phase Shift Key
PTP	Point-to-Point
RBU	Radio Base Unit

RESS/REP	Radiant Edge Switch System/Radiant Edge Processor
RTS	Roof-Top-Systems
SN	Seed Nodes
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TNCP	Trunk Network Connection Points
TDMA	Time Division Multiple Access
VBR RT	Variable Bit Rate- Real time
VBR NRT	Variable Bit Rate- Non Real time
UBR	Unspecified Bit Rate
UDP	User Datagram Protocol
UHF	Ultra High Frequency

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EXECUTIVE SUMMARY

Last-mile technology is any telecommunications technology, such as wireless radio, carrying signals from the broad telecommunication along a relatively short distance to and from the home or business. Driven by today's demands of larger bandwidth in both business and residential sectors, new initiative wireless broadband technologies have been proposed as a solution to the "last-mile" problem.

Emerging technologies that fall under the category of broadband wireless include Local Multipoint Distribution Systems (LMDS), Free Space Optics (FSO) and High Altitude Long Endurance (HALE) systems. First, LMDS is a broadband wireless point-to-multipoint communication system operating above 20 GHz (depending on the country of licensing) that can be used to deliver voice, data and video. Second, FSO networking is a technology that delivers extremely high data rates through optical signals using free space as a medium. Finally, HALE is a telecommunications relay station carried by an aircraft or an aerial platform.

Today, all these technologies are both technologically and economically viable as evidenced from the numerous new companies that offer or will offer broadband wireless services in the near future. Certainly, these technologies will have a significant impact on the competitive landscape of broadband telecommunications. However, the information currently available for these systems is essentially promotional material. In addition, lack of standardization and rapid technological advances characterize these networks. Therefore, technological claims and counterclaims often confuse and mislead by hiding and/or providing incorrect information requiring an objective assessment in these systems a necessity.

This thesis provides an objective in-depth study of emerging wireless broadband systems emphasizing technological and business aspects. Network architectures are explained and compared addressing the pros and cons of each approach. Propagation issues also are discussed and a link budget analysis is developed for each system. Furthermore, the system's coverage and capacity is analyzed for each technology.

Based on the above study a comparison of potential solutions for the "last mile" problem, both wired and wireless was also given. The main benefits of wireless versus wired technologies are ease and fast deployment, lower deployment cost, demand-based buildout and better performance in terms of bandwidth. Although xDSL and cable networks are the dominant technologies in providing broadband services today, emerging wireless broadband technologies is expected to grow from a nascent technology to a strong niche player in the broadband market over the next years.

Deploying a wireless network is a difficult task that requires more than an understanding of the technological concepts. This thesis develops a deployment strategy for LMDS and FSO systems by dividing the areas of interest into three categories: identifying the target market, developing the business case and deploying the network. This strategy organizes the ideas in a practical point of view and describes, in a step-by-step format, the major considerations and critical issues in deploying these networks.

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I. INTRODUCTION

A. MOTIVATION

The need for broadband network access in small size networks, as in metropolitan areas, is experiencing rapid growth. This results in the well-known “last mile” access problem, which has paved the development of many new innovative technologies. A wireless approach is the most promising technology in providing broadband services in both the commercial and residential sector. Wireless broadband technologies are attractive for their low cost, quick installation and inherent flexibility when compared with wired access systems. However, as with all of the newest technologies, the lack of standardization and the risks involved in being the pioneer of an emerging market have contributed to a relatively slow commercialization of such technology.

Emerging technologies that fall under the category of broadband wireless include Local Multipoint Distribution Systems (LMDS), Free Space Optics (FSO) and High Altitude Long Endurance (HALE) systems. First, LMDS is a broadband wireless point-to-multipoint communication system operating above 20 GHz (depending on the country of licensing) that can be used to deliver voice, data and video. Second, FSO networking is a technology for delivering extremely high data rates through optical signals using free space as a medium. Finally, HALE is a telecommunications relay station carried by an aircraft or an aerial platform. Today, all these technologies are both technologically and economically viable as evidenced from the numerous new companies that offer or will offer broadband wireless services in the near future. Certainly, these technologies will have a significant impact on the competitive landscape of broadband telecommunications.

However, the information currently available for these systems is essentially promotional material. Many large companies like Alcatel, Nortel, Lucent and Cisco compete for a high market share and by trying to persuade the telecommunication community that their product or service is the best. This results in technological claims and counterclaims that often confuse and mislead by hiding and/or providing incorrect information. Additionally, the companies’ high interest in this area leads to rapid

technological advances making existing systems and proposed technologies outdated. Thus, a need for an objective assessment of these systems is very important.

The motivation behind this thesis is to address technological and business aspects of these emerging broadband technologies since it is expected to have a significant impact on the design and standardization of tomorrow's commercial wireless networks. Undoubtedly, these technological advances will also have a significant impact on the design and development of advanced military wireless communication systems.

B. OBJECTIVES

The objective of this thesis is to provide an in-depth study of emerging wireless broadband technologies that have been proposed as a solution to the "last mile" problem. More specifically, research goals can be summarized as follows:

- Provide an objective assessment of wireless broadband systems.
- Compare alternative technological solutions and approaches in each emerging wireless broadband system.
- Compare emerging wireless technologies with other competitive technologies aimed in solving the "last mile" problem.
- Develop a deployment strategy for wireless broadband systems.

C. ORGANIZATION OF REPORT

This thesis is organized as follows: chapter II discusses LMDS systems by first giving a background of the existing technologies and, then, by comparing different technological options in network architectures, network design and capacity. Propagation issues are also addressed for millimeter waves; a link budget analysis is also developed. Chapter II introduces FSO, another emerging wireless broadband technology. Comparisons between technological alternatives and a link budget analysis in a similar way to the LMDS systems are provided. Furthermore, special issues like safety for these systems are presented. Chapter III describes the HALE systems for purposes of completeness with respect to emerging wireless broadband technologies. Chapter IV

presents a comparison among all the competitive broadband technologies (wired and wireless) that are candidates for solving the “last mile” problem. Chapter V develops a deployment strategy for wireless broadband systems. Chapter VI provides concluding remarks and suggestions for future research.

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II. LOCAL MULTIPOINT DISTRIBUTION SERVICES

A. OVERVIEW

The Local Multipoint Distribution Services (LMDS) systems is a relatively new type of terrestrial wireless services providing an attractive solution to the “last mile” problem of connecting consumers to the broadband communications. The system operates in millimeter frequencies, above 20 GHz (depending on country of licensing) and can be used to provide full-duplex high data rate voice, data, Internet, and video services.

In 1998, the Federal Communication Commission (FCC) carried out a nationwide auction of the wireless LMDS spectrum in the 28-31 GHz frequency range. In each geographical area, the FCC auctioned an “A block” bandwidth of 1150 MHz and a “B block” of 150 MHz. This is the largest bandwidth ever auctioned with twice the total bandwidth of AM/FM radio, VHF/UHF TV, and cellular telephone combined. This kind of wireless broadband services is not confined only to the USA but rather it is worldwide. Many other countries have allocated LMDS spectrum such as Canada, Venezuela, Korea, Romania and European countries.

Since 1998, numerous companies in the USA hold licenses in the LMDS spectrum. Winstar, Teligen and XO Communications are the larger companies and they have deployed LMDS systems in many areas within the country. Additionally, many vendors working in this continuously changing technological area are trying to establish standards. Alcatel, Nortel, Ericsson and Netro are the biggest vendors providing cellular like LMDS systems. However, a small company, named Radiant Networks in England, claims it is ready to deploy LMDS systems using a mesh architecture, which results in substantial economic and performance benefits.

Several other challenges also exist in LMDS as choosing a Medium Access Control (MAC) technique, duplexing method, modulation scheme, and other networking issues. System integrators have not been able to give answers for these key design issues that could severely affect the performance of an LMDS system. The following

subsections discuss all the above-mentioned areas along with a comparison of the basic design choices by highlighting the advantages and disadvantages of each approach.

B. NETWORK ARCHITECTURES

Typically, network topologies for LMDS systems are Point-to-Point (PTP) or Point-to-Multipoint (PMP). However, a new innovative technology, the mesh architecture, has appeared. These competing technologies have significant differences in operation and performance issues. The following sections provide a detailed analysis of the PMP and mesh architecture in order for the basic concepts to be understood. However, PTP is not examined in detail since it is the simplest approach and a mesh topology uses point-to-point connections. Finally, a comparison of all the above technologies is provided.

1. Point-to-Multipoint (PMP) Architecture

This architecture based on a cellular design typically consists of three parts: Base Station (BS), Radio Base Unit (RBU) and Customer Premises Equipment (CPE). The end users link to the base stations that in turn, link to the wireline Internet and Public Switched Telephone Network (PSTN). Figure 1 illustrates a possible PMP LMDS system.

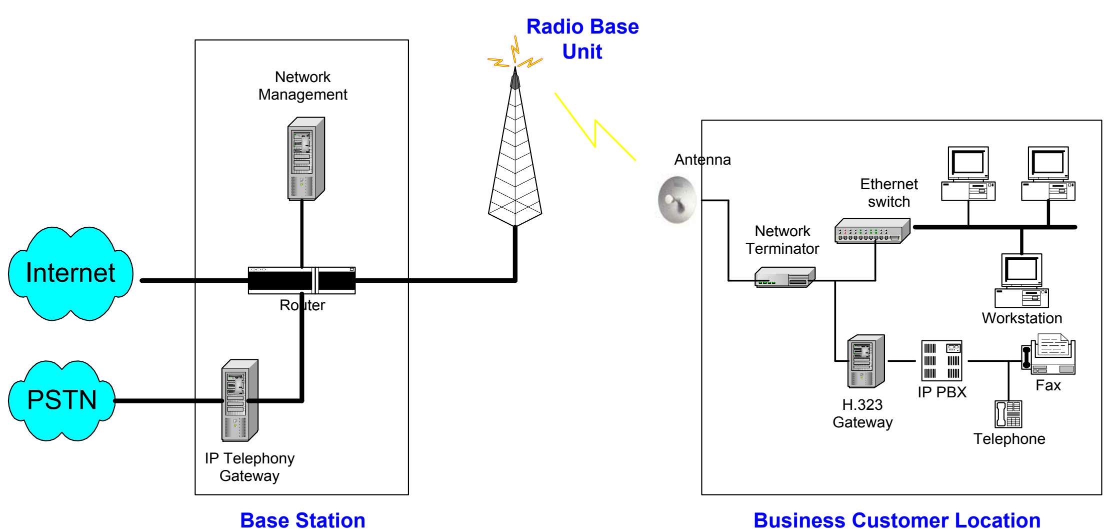

Figure 1. A PMP LMDS architecture.

The BS is the digital part of the LMDS access solution and is interconnected with the Internet and Public Switched Telephone Networks (PSTNs). It contains routers, network interfaces, modulators, demodulators, servers and the network management unit (NMU). The NMU is the centralized intelligence for the whole cell organization that provides the ability of supporting and offering a broad range of services.

The RBU is the linking point between end users and the backbone network. It consists of a sector antenna and usually separates receiver and transmitter. More than one RBU may be connected to one BS. For example, in the Alcatel 7390 LMDS system up to eight RBSs can be connected to the same BS [4]. Also, the RS is fully managed from the network management unit.

The CPE configurations differ from vendor to vendor. Typically, CPEs consist of outdoor-mounted microwave equipment and indoor network terminator. The microwave equipment consists of a transceiver integrated with a high gain antenna. The radio terminator provides modulation, demodulation and customer-premises interface functionality.

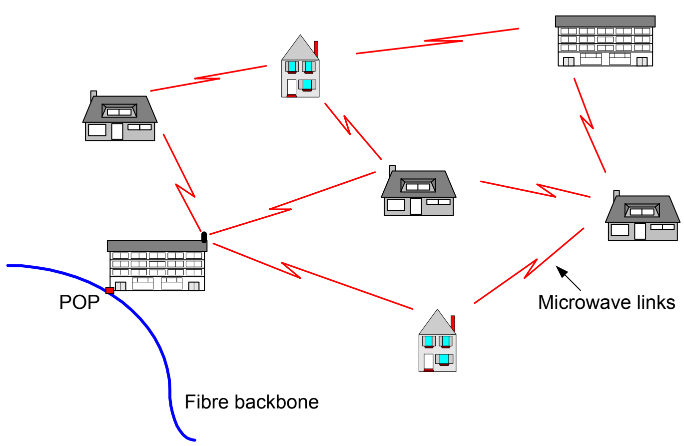

Figure 2. Mesh layout overview.

2. Mesh Architecture

A mesh network comprised of customer terminal or nodes that transmit and receive to and from other nodes [5]. Each node may communicate with more than one

neighbor node and typically up to four other nodes. In other words the nodes receive, transmit and forward traffic. The radio links that connect the nodes are point-to-point and highly directional. Figure 2 illustrates typical mesh network architecture.

In addition to nodes deployed at customer premises, a mesh network requires a number of system nodes. These nodes are the Radiant Edge Switch System and the Radiant Edge Processor (RESS/REP), the Trunk Network Connection Points (TNCPs), the Mesh Insertion Points (MIPs) and the Seed Nodes (SNs). Figure 3 presents an overview of a mesh architecture and its components.

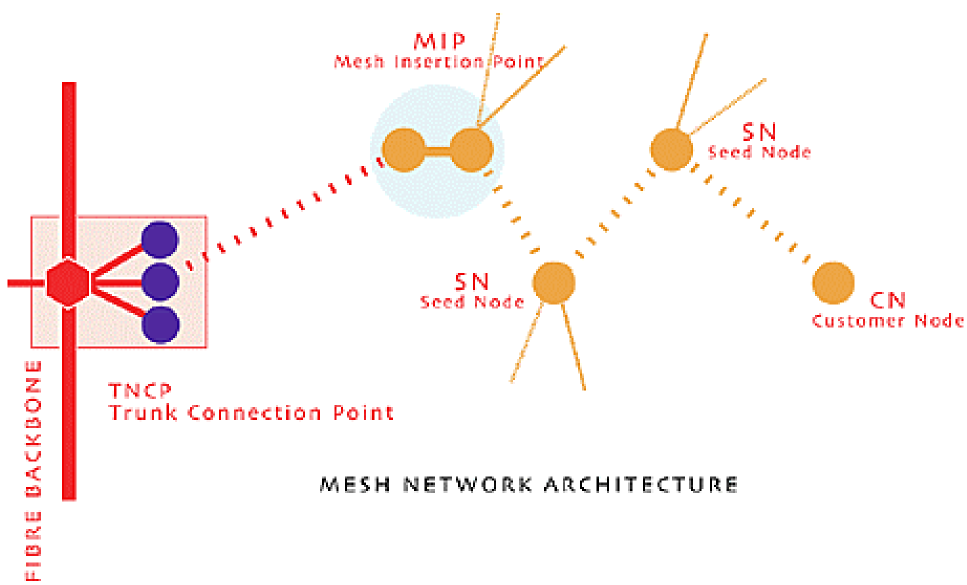

Figure 3. Components of a mesh network architecture (From Ref. [5]).

The RESS/REPs interconnect the mesh network with the core network. In the Radiant mesh system, RESS/REP is a commercial ATM switch. This non-radio system node aggregates and manages the traffic from and to the mesh network providing edge-to-edge services within the mesh network like ATM virtual circuit switching and routing, and alternative route selection. Typically a RESS/REP node is able to support up to 10 TNCP nodes.

The TNCPs are the points at which data are transferred into the network or, as they commonly referred to the bottlenecks that introduce traffic into the mesh. These

radio nodes handle high data rates like 155 Mbps, and may feed more than one MIP. a TNCP node typically supports up to 5 MIPs.

The MIPs are the points at which the mesh starts to grow. These MIPs consist of one high-speed node connected to the TNCP and one or more other nodes linked with subscriber nodes within the mesh network. The distribution of MIPs should balance the traffic flow across the predicted future mesh so that local bottlenecks do not limit the performance of the mesh.

The SNs are similar with the customer nodes but placed away from the operator in order to provide additional coverage and customer penetration. That means these nodes operate as simple repeaters by receiving and forwarding traffic. Their main purpose is the initial mesh network to be able to support a large area. As the number of subscribers within a specific mesh area increases, the number of required SNs decreases.

3. Comparison of Network Architectures

Currently, almost all the LMDS operators utilize PTP and PMP systems. In the U.S., PTP is the majority share of LMDS surrendering the rest of the market to PMP. In contrast, PTM topologies are more favorable in Europe and many other areas worldwide as evidenced by Alcatel's claims that more than 600 networks and 6,000 base stations have been deployed. On the other hand, mesh architecture seems to be very promising; although, it has not tested yet. Today, Radiant, the English company that introduced the mesh concept deploys networks and evaluates them in Virginia in USA and in Spain.

Comparatively, PTP networks are less expensive than the PMP systems with respect to the initial cost and to small number of subscribers. However, as the number of customers increases, the PMP architecture will be more economical. Since by nature LMDS support many customers, PTP systems are unique cases which are preferable only when the market target refers to a few customers with large bandwidth demands. Therefore, the rest of this section compares the other two architectures, PMP and mesh.

One of the most important factors in LMDS systems is the Line of Sight (LOS) requirement. Although in cellular mobile communications near-LOS is not a problem, in

high frequencies in which LMDS systems operate, clear LOS is necessary. When considering a PMP approach, a cell based system, studies show that up to 30% of the potential subscribers may not be reachable due to LOS limitations in an urban area. This coverage shortfall can be overcome by using mini-cells to cover some dark areas. However, the cost of the additional base stations and the associated backbone connections is significant. In contrast, mesh networks overcome the LOS limitations because a customer needs to see at least another customer instead of a base station. Furthermore, seed nodes can be used as intermediate nodes when the density of customers is not adequate.

Another important factor is the associated cost of each approach. Mesh vendors claim that the cost is significantly lower than the classical PMP solution. This is due to the fact that a mesh is a “peer-to-peer” network, using the same low-cost equipment to connect to the trunk network as it does to connect customers. Thus, no demand for expensive base stations exists. Moreover, these inexpensive nodes that feed the mesh can be located at the trunk network point of presence. In contrast, base stations typically are located at the top of hills or high buildings and additional costs of fibre connections to the base sites are often necessary.

Finally, mesh networks improve the link availability due to the inherited redundancy since data can be routed between two points using many different paths. In contrast, in PMP systems only one single radio link exists to the base station, which is a single point of failure. In addition, in mesh architectures, the capacity can be increased through multiple link support. However, today’s mesh networks provide a peak subscriber data rate of approximately 25 Mbps per user.

Based on the above discussion a question arises as to whether the mesh architecture is the best solution. Despite the fact that mesh is a very promising next-generation technology, it has not yet been broadly tested. The company has to show that the technology works as promised delivering the advantages it claims to provide. Additionally, the PTM systems continue to be refined and improved, resulting in lower prices and more capabilities. Thus, the technological advances in these two architectural approaches determines the technology that will dominate in the future. Moreover, PTP

connections will continue to exist whenever large bandwidth demands for one customer is necessary. Ceragon, for example, provides equipment that supports OC-12 links, which are much higher than the maximum of 40 Mbps and 25 Mbps per end user of the PTM and mesh approaches.

C. PROPAGATION ISSUES

The radio channel is a hard environment and varies from simple line-of-sight (LOS) to one that has obstacles, like buildings or mountains. Modeling and predicting a wireless channel is very challenging and, historically, these have been one of the most difficult parts of radio system design.

This section discusses the main factors that influence the propagation of waves at the millimeter wavelengths in which the LMDS systems operate. In addition, this section develops a link budget analysis.

1. Main Considerations in LMDS Systems

The term Line of Sight (LOS) means that a light at the transmitter is visible at the receiver. In many cases the transmission loss in LOS radio waves is different than the free space loss due to reflection, diffraction and refraction.

In LMDS systems, due to their specific characteristics, multipath fading is not an important issue. First, LMDS systems are operated above 10 GHz, therefore they are strictly LOS communications systems. The maximum propagation distance is also typically less than 5 kilometers. In addition, the antennas are high enough, in the rooftops, and highly directional with vertical coverage 2°-5°. All these factors combined result in further reduction of the multipath effects. Last, but not least, the antennas of these systems are in fixed positions, therefore a little improvement can be done by changing the location of an antenna.

2. Link Budget Analysis

The Friis free-space equation is commonly used to predict received signal strength when the transmitter and receiver have a clear line of sight path between them.

However, this model is accurate only in the range of frequencies between 500 MHz and 1 GHz. For systems operating in millimeter waves, like LMDS, the total path loss is given by Freeman [8] as follows:

$$(\text{Total PL})_{dB} = 92.467 + 20\log_{10}(f_{GHz}) + 20\log_{10}(D_{km}) + (\text{Excess Attenuation})_{dB} \quad (2.1)$$

where,

$(\text{Total PL})_{dB}$ is the total path loss between transmitter and receiver

(f_{GHz}) is the operating frequency

(D_{km}) is the separating distance between the transmitter and the receiver

$(\text{Excess Attenuation})_{dB}$ is a loss factor for molecular resonance and precipitation

The difference of the above formula with the simple free space propagation model is the factor of excess attenuation. This loss factor considers additional losses in the case of millimeter waves, that is: absorption due to gasses or water vapor and attenuation due to snow, fog or rainfall.

Many gasses and pollutants have absorption lines in the millimeter band but, due to their low densities, do not generally affect LMDS systems. However, water vapor, which has an absorption line of 22.235 GHz, mainly causes the absorption loss. The amount of loss due to water vapor is larger especially in areas of humid climates in which 30 grams per cubic meter is possible. A typical value for path loss using the oxygen absorption and 100% humidity is 2 dB.

On the other hand, snowfall and fog do not affect the propagation of waves as much as rainfall. Snowfall rates are generally less than rainfall rates and fog consists of very small particles with respect to the millimeter waves. Rainfall is the most significant atmospheric effect that has to be considered when an LMDS system is designed. The wavelengths in frequencies between 10 GHz to 38 GHz are comparable with the size of raindrops; therefore, scattering and attenuation is possible. Moreover, rainfall causes depolarization of the transmitted signals decreasing the received signal power.

The above path loss analysis allows this link budget equation:

$$C/N = P_t + G_t + G_r + A_t + A_r - (\text{Total Path Loss}) - F - 10\log(B106)$$

The components of the equation, as explained in Table 1, can be use as guidelines for calculating of the total power received and whether the design has the necessary margin in received signal strength in order to achieve the required link quality. A sample link budget analysis with typical values is also provided.

Parameter	**Value**	**Umits**
Frequency (f)	40	Ghz
Transmitted power (P_t)	-5	dBW
Transmitter gain (G_t)	15	DB
Transmitter feeder losses (A_t)	0	dB
Receiver gain (G_r)	35	dB
Receiver feeder losses (A_r)	0	dB
Separate distance (path length) (D)	3	km
Percentage of unavailable time	0.01%	---
Attenuation due to rain exceeded for a given percentage of time (Arain)	28	dB
Absorption due to gasses (Agas)	1	dB
Receiver noise figure (F)	6	dB
Radio channel bandwidth (B)	33	MHz
Target signal-to-noise ratio At the demodulator input (C/N)	7	dB

Table 1. Link budget example for LMDS systems.

In this table the maximum distance is 3 km from the base station with the unavailable time of 0.01%. Note that the rain attenuation depends on the required unavailable time, which is given using the ITU model. By repeating the above calculations for the required unavailable time of 0.1%, the maximum allowed range increases to approximately 5 km. That means the required availability significantly affects the cell coverage from a base station. These calculated distances are approximate

since they depend on details specific to each vendor's system design and on the rain region.

D. SYSTEM COVERAGE AND CAPACITY

1. Medium Access Methods

The LMDS systems are generally multipoint systems and, thus, multiple access methods are required. Each method aims to better utilize the radio spectrum by allowing multiple users to share the common physical channel. The three primary access schemes for wireless systems are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). Among them, TDMA and FDMA are the most common schemes currently used in LMDS systems. However, CDMA is a very promising technology as evidenced from the adoption of this technology in 3G cellular networks. The next paragraphs provide an overview and a theoretical comparison these competing technologies.

a. *Overview of TDMA, FDMA and CDMA*

The TDMA methods divide the radio spectrum into time slots and in each slot only one user is allowed either to transmit or receive. This results in a burst transmission of data periodical instead of continuous one, because data are buffered in the transmitter. The transmitted data are organized into TDMA frames. A typical frame format is illustrated in Figure 4; however, different wireless standards exist that have different frame structures. Each frame contains a cycle of time slots with one or more slots capable of being allocated to each end user. The preamble provides address and synchronization information while guard times are used to allow synchronization of the receivers between different slots and frames.

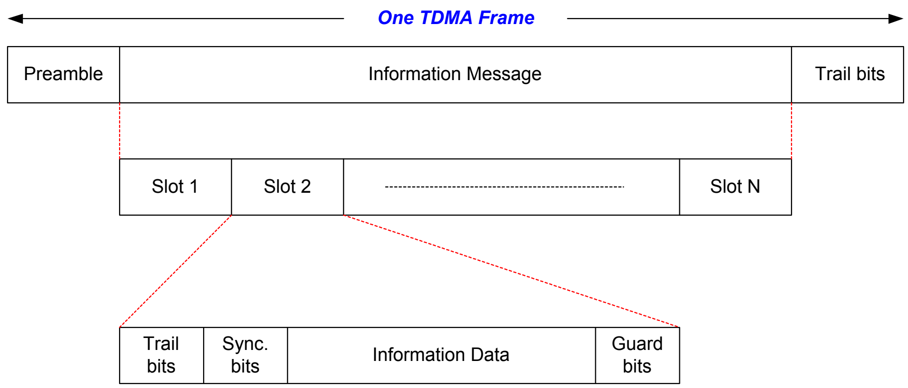

Figure 4. TDMA frame structure (After Ref. [2]).

The FDMA methods divide a given radio spectrum into smaller frequency bands, called subdivisions. Each subdivision has a unique IF carrier frequency and each channel can be assigned only to one user at a time. In addition, FDMA schemes have to allocate guard bands that utilize spectrum inefficiently. The guard bands protect the system from interference by other users.

The CDMA methods are based on spread spectrum multiple access techniques. More specifically, each user generates data, for example, the output from a speech coder, and this narrowband message is multiplied by a spreading signal to achieve the final output signal. The spreading signal is a pseudo-noise code sequence that has a chip rate many times larger than the data rate. The codeword is also unique for each user. As a result, users can transmit simultaneously with the same carrier frequency.

b. Duplexing Methods

Since LMDS are full duplex systems, simultaneously transmission and reception between the base station and the end users is required. Thus, duplexing methods for separation of the up and down streams must be applied. The two common methods are called Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD).

The TDD systems operate in a similar fashion to TDMA systems. The uplink and downlink use all the available bandwidth during transmission but only in

specified time periods as illustrated in Figure 5. Asymmetrical time slot allocation is possible for better utilization of the bandwidth, as uplinks typically require lower data rates. On the other hand, FDD systems provide two-way communication by separating the bandwidth into two smaller channels, one for reception and another for transmission. As in the TDD method, efficient use of the spectrum is feasible with asymmetrical bandwidth allocation for the two different channels. Generally, in the base stations in FDD based systems, two separate transmitting and receiving antennas are used. In contrast, at the end user's site only one antenna is used for both transmission and reception. Therefore, a device, called a duplexer, is required to separate the two channels.

In wireless communication systems, both the multiple access and the duplexing methods are used in order to characterize the radio interface. Note that all the above multiple access methods are able to use either TDD or FDD. Thus, for example, the resulting TDMA schemes are called TDMA/TDD and TDMA/FDD corresponding to the two different duplexing methods.

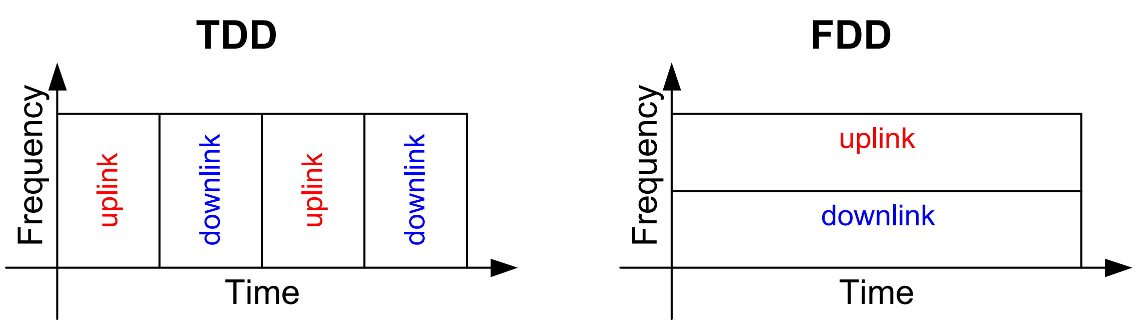

Figure 5. TDD and FDD methods.

c. *Comparison of Multiple Access Methods*

The above-mentioned multiple access schemes have advantages and disadvantages. This section provides an in-depth analysis considering the particular characteristics of LMDS systems. First, the multiple access schemes are compared followed by the duplexing methods. Finally, possible implementations are discussed.

Currently the majority of system operators have adopted the TDMA and FDMA approaches. Nortel, one of the leading companies in providing end-to-end LMDS

solutions, offers both FDMA and TDMA systems. Another leading company, Alcatel, also offers the 7390 LMDS, which is based on TDMA. Due to adopting the TDMA and FDMA approaches, the comparison focuses mainly on these schemes.

Both TDMA and FDMA systems are able to provide bandwidth on demand. In FDMA, frequency slots are allocated dynamically to different users while in TDMA time slots are concatenated or reassigned.

The main advantages of FDMA over TDMA are as follows: (1) easier to be implemented, (2) less sensitive to fade and interference and (3) less overhead per frame. The FDMA method is simpler because it is a long available and a well-known technology. Also TDMA requires more complex subscriber units for synchronization and equalization purposes. The equalizer is used in TDMA systems in order to overcome the intersymbol interference (ISI) at the receiver. In FDMA, the ISI is low because the symbol time is large compared with the average delay spread. Therefore, FDMA allows higher modulation schemes, resulting in higher capacity. Finally, TDMA requires high synchronization overhead since the transmission of data is bursty.

On the other hand, the main benefits of TDMA schemes are (1) lower cost and (2) a more efficient spectrum. First, FDMA systems require costly bandpass filters. They also typically use separate power amplifiers for each channel before passing the signals through an expensive high power combiner and then being transmitted from the antenna. Another possibility is to use a highly linear amplifier and to combine the signals before the amplifier; however, these amplifiers are extremely expensive. Moreover, TDMA systems do not require duplexers even if FDD is used; additionally, only one modem is needed per carrier at the base station. The reason of better spectrum efficiency in TDMA based systems compared to FDMA is the size of the guardband relative to the size of a burst which is smaller than the size of the guardband effectively required for FDMA relative to the bandwidth of an FDMA channel [3]. In addition, by using an adaptive TDMA scheme, the performance can be further improved.

The third access method, CDMA, is claimed to provide much higher capacity than TDMA. This is true, but for broadband applications, like LMDS, CDMA is generally not appropriate. If a customer requires a connection of 5 Mbps and a typical

spreading factor of 64 is used, the resulting total bandwidth required is 320 Mbps. With both uplink and downlink, the total required bandwidth would be approximately 640 Mbps, depending on the modulation scheme used. This scenario results in two problems. First, not many operators have such a large bandwidth, and second, all the bandwidth dedicated to one channel is not efficient. Note that for higher than 5 Mbps data rates the problems are becoming worse. A solution is multicode transmission in which users may have more than one code at the same time. However, this increases the complexity and cost of the system, requiring a separate correlator and decoder at the receiver.

Based on the above, TDMA is a better approach as it is less expensive and provides a higher capacity than FDMA in an inherited bandwidth limited environment. However, there are cases where a FDMA access method is better. For example, if there are few end users with high data rates, the adoption of FDMA or a combination of FDMA and TDMA would be more efficient.

2. Modulation Schemes

Modulation is the process of encoding information into the amplitude, phase, and/or frequency of transmitted signal. This allows the information to be transmitted through the medium. The two modulation techniques used in LMDS systems are Phase Shift Key (PSK) and Quadrature Amplitude Modulation (QAM). Both methods have advantages and disadvantages. The choice of the encoding process is a matter of capacity, interference and efficiency.

The PSK techniques involve the change of the phase of a waveform with these finite phase changes representing digital data. The simplest form is the Binary PSK (BPSK) in which a phase-modulated waveform is generated by using the digital data to switch between two signals of equal frequency but in opposite phase. However, the BPSK scheme caries only one bit per symbol, which results in low efficiency in terms of data rate. The LMDS systems often use four separate phase states (eg. 45°, 135°, 225° and 315°) in the scheme called Quadrature PSK. Since there are four possible phases, there are two bits of information conveyed within each symbol. Therefore, QPSK is more

bandwidth efficient than BPSK, but it is still not as efficient as other modulation schemes, such as 16 and 64-QAM.

The QAM techniques involve changing both the phase and amplitude of a waveform. These methods take advantage of the fact that the greater the number of bits per symbol, the greater the efficiency of the system. The most common scheme is 16-QAM in which four bits per symbol are transmitted. However, higher QAM schemes are available providing even better efficiency like 64-QAM and 256-QAM schemes.

Since LMDS systems operate in wireless channels, which are inherently bandwidth limited, the choice of a modulation scheme with high capacity is very important. Techniques with 16 and 64-QAM can, in theory, accommodate two and four times the bandwidth available through QPSK on the same spectrum. Although these schemes appear to be very attractive for LMDS systems, in practice, there are some limitations. The higher density modulation allows greater data throughput rates at a given power but decreases the maximum transmission range. In addition, LMDS systems are multi-cell networks with the same frequency channels reused frequently on adjacent cells. This results in larger interference when higher density modulation schemes are used.

Currently the majority of the existing LMDS vendors provide systems that use QPSK modulation because these systems (1) optimize the coverage area and the number of cells (2) maximize frequency reuse (3) minimize areas of interference. More specifically, PSK compared with the 16-QAM [4] provides 2.5 times greater surface coverage per cell and only 25% of the interference with the same cell radius. Moreover, only 25% is required because of the smaller reuse pattern. For example, in the QPSK scheme there are four carriers instead of 16 carriers. Additionally, the required number of cell for coverage of the same area is one quarter for the QPSK scheme. Considering all of the above and according to Alcatel and ETSI Standards, the resulting efficiency of QPSK is 150% higher than the efficiency of 16 QAM and the use of only 64 QAM since a modulation scheme is impractical.

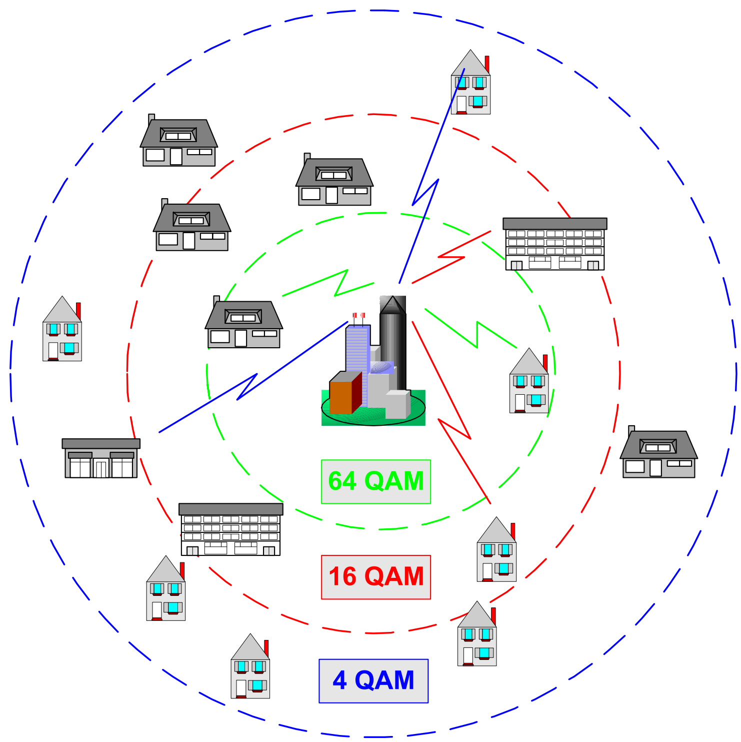

Figure 6. Adaptive modulation scheme in LMDS systems.

However, the selection of a single modulation scheme is a waste of limited system resources. The reason is simple that you have to consider the worst-case wireless channel scenario in order to satisfy the reliability requirements. Due to this, many manufacturing companies of LMDS systems see the graduating modulation level systems as a promising approach for the next generation LMDS systems. These systems will divide each cell into three areas and provide three different bandwidth levels from the center to the edge through an auto-adaptive 64/16/4 QAM modulation scheme. Figure 6 illustrates a possible architecture of adaptive modulation. The unique feature in LMDS that are fixed wireless systems makes this approach feasible. The separation distance between the base station and the end-users is known in advance and, therefore, the proportion of channel loss due to distance is known in advance.

3. Design issues

The performance of LMDS systems is highly affected by the coverage and the capacity within an area. Both the coverage and the capacity depend on the location of the base systems or wireless nodes and the other technical aspects of the system. Also, each architecture approach, PMP and mesh, requires different factors for the network planning.

a. PMP Cell Design

The PMP LMDS systems follow a cell-based approach similar to mobile cellular networks. The first thing to determine is the maximum cell size. This is done using the link budget analysis presented in previous sections. Therefore, the approximate maximum distance depends on the desired reliability, attenuation factors and modulation scheme used. Typically maximum transmitting distances for PMP systems are 3-5 km.

Also, a technique called frequency reuse is used in order to minimize interference between the subscribers and hub-stations. Typically, systems adopt a 60 or 90 degrees sectorization. Moreover, various reuse patterns are possible. Figure 7 depicts two possible PMP cell reuse patterns. In the hexagonal approach, the frequency allocation scheme requires three times the bandwidth allocated to one cell. In the rectangular approach, four different frequencies are used. Furthermore, polarization is another technique that increases the capacity of the network. In this technique, the antenna's polarization alternates between horizontal and vertical. A frequency reuse of two using polarization can support a four-sectored cell as depicted in Figure 8.

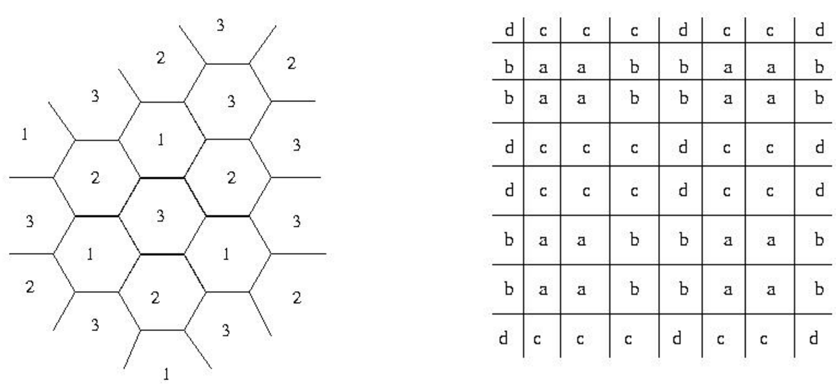

Figure 7. Two possible cell reuse plans in LMDS systems. A hexagonal approach (left) and a rectangular approach (right).

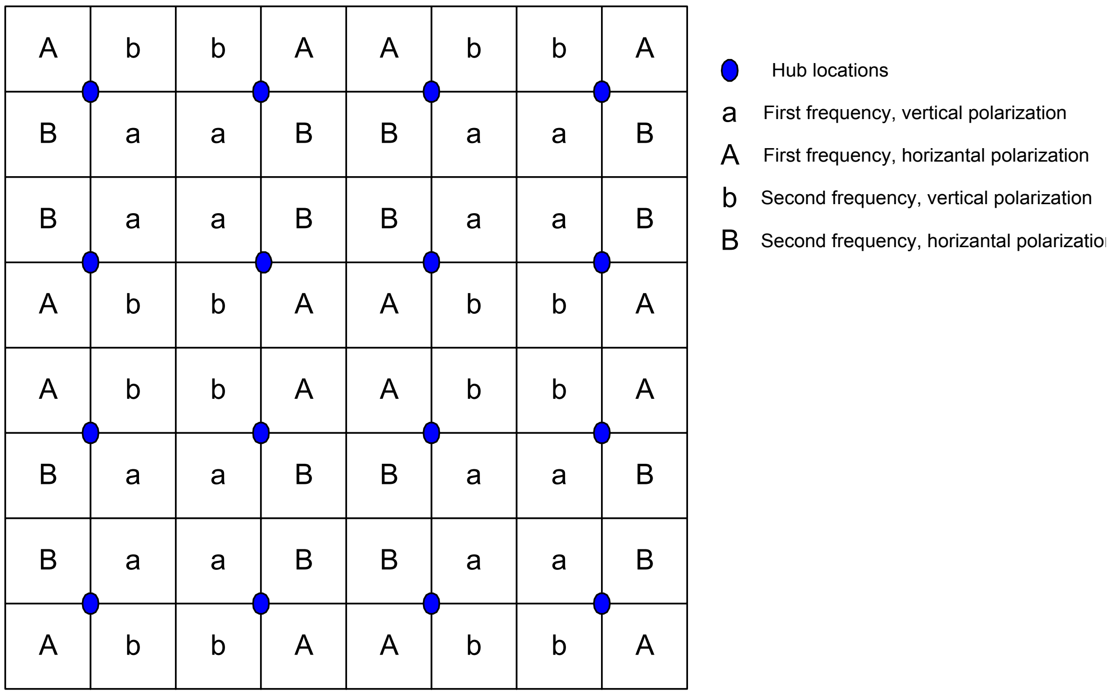

Figure 8. An LMDS frequency plan of frequency reuse of two using polarization.

b. Mesh Design

On the other hand, the deployment of a mesh network does not require so much design effort before the installation because the capacity and coverage are achieved independently. More precisely, the subscribers provide the coverage and the total number of trunk nodes for capacity. Typically, a low capacity for the network is preferable with trunk nodes being added as the network grows. The maximum distance between two nodes is 1-2 km.

Mesh networks utilize point-to-point connections with narrow beams, only 9°, nevertheless, interference can occur. Figure 9 illustrates the situation in which interference between two nodes is possible. Presumably, that radio links (A) and (b) are on the same time slot and also link (a) is within the node “1” antenna field of view. According to a theoretical analysis by Radiant, the number of possible interference within the mesh is approximately proportional to the square of antenna beamwidth [6]. This problem is solved spatially by the antenna ’s locations not generating the interference

shown in Figure 9. Other solutions are either to select appropriate timeslots or an alternative channel so that interference is avoided.

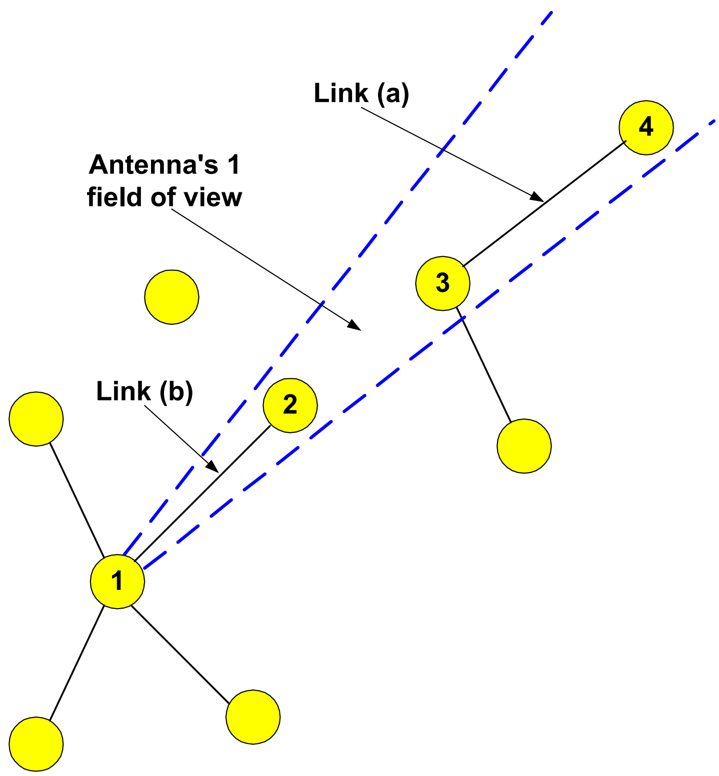

Figure 9. Possible interference within a mesh (After Ref. [6])

c. Comparison of Designs

The mesh design provides significant advantages compared to PMP cell design. The most important advantage is the simplicity of the initial design since the location of the trunk nodes introducing traffic into the mesh are not required to be at a specific position. In contrast, PMP systems have to account for the larger coverage based on LOS limitations. After the initial installation, as the network and traffic demand grows, PMP systems have, once more, many problems to overcome. These problems, explained in the following paragraph, are related with the scalability of the network.

Generally, PMP LMDS systems are initially planned in order to cover a large area using macro cells. Furthermore, new customers often degrade the service to

existing customers. Thus, as the number of subscribers becomes large enough, a need for splitting the network into smaller cells, called micro cells, exists. This requires re-engineering the network, which is a very difficult task. The new hub locations have to be fiber connected to the core network and also satisfy the larger possible coverage in terms of customers within the new cell. Moreover, antennas of existing subscribers have to be re-directed and probably re-polarized. Finally, upgrading the network can cause temporary disconnection for some of the subscribers for a short period of time. On the other hand, mesh networks are much simpler pertaining to the scalability. As the traffic demand increases, trunk nodes can be added to the network increasing the capacity. Trunk nodes can also be located at the fibre point-of-presences (POPs) since spreading them within the network is not required. Trunk nodes only provide traffic without coverage like the base stations in PMP systems.

The above comparison shows the superiority of the mesh networks. However, note that mesh performance and layout of the network based on a theoretical analysis as broadly commercial tests are performed nowadays. In contrast, PMP systems are commercially tested with cell design issues being addressed years ago in the similar mobile cellular networks design.

4. Capacity of LMDS Systems

LMDS system capacity can be measured in terms of data rate and maximum number of subscribers. These two metrics are primarily affected by two factors: the available bandwidth and the spectral efficiency. This section provides general guidelines for calculating the system capacity for both PMP and mesh approaches.

In order to calculate the capacity of a PMP system, a simple scenario is assumed. The total usable spectrum is 2,000 MHz and a frequency reuse of two is used. It is also assumed that symmetrical bandwidth for both directions and 5 MHz FDMA links are utilized. The total capacity per cell can be computed using the following equations:

(usable spectrum per sector) = (total usable spectrum) / (frequency reuse)

(sector capacity) = (usable spectrum per sector) × (spectrum efficiency)

(capacity per cell) = (# of sectors) × (capacity per sector)

(number of customers) = (usable spectrum per sector) / (bandwidth of FDMA links)

The usable spectrum per sector in our example is 2,000 / 2 = 1,000 MHz. This gives a usable spectrum per sector per direction of 1,000 / 2 = 500 MHz. The spectrum efficiency depends on the modulation scheme, which is 1.5, 3.5 and 5 bits/second/Hz for the QPSK, 16-QAM and 64-QAM schemes respectively. Thus, the corresponding sector capacity for each modulation scheme is 750, 1,750 and 2,500 MHz per sector per direction. Since two sectors have been assumed, the cell capacity per direction is 1,500, 3,500 and 5,000 for the three modulation schemes. As expected, the larger capacity is given using 64-QAM because of the larger spectral efficiency. Finally, the number of maximum customers supported by the system is 500 / 5 = 100 for each sector for all the modulation schemes. However, the providing capacity is 7.5, 17.5 and 25.0 MHz per customer in both upstream and down stream for the QPSK, 16-QAM and 64-QAM respectively. Note the calculated capacity is an approximate since factors like guardbands have not been considered due to simplicity. Additionally, although the 64-QAM modulation scheme is very attractive and provides the higher capacity, it is implemented only within very short distances, as explained in previous sections.

On the other hand, the capacity of a mesh network is difficult to measure. Generally speaking, mesh networks are expected to provide much more capacity. The main reason is that mesh networks utilize very narrow radio beams, only 9°; therefore, the interference is lower within a specific area, resulting in larger spectral efficiency. In addition, an increase in the number of subscribers does not degrade providing service to the rest of the customers and scalability is much easier as the network grows. According to theoretical analysis and detailed modeling from the company proposing the mesh systems, assuming 2×112 MHz FDD allocations (8×28 MHz TDD/TDMA channels), the Radiant Mesh can deliver duplex traffic of 5 Mbps to more than 200 subscribers with a peak data rate of 25 Mbps [6].

E. OTHER ISSUES

1. Networking Issues

The majority of today's LMDS systems have adopted ATM technology as an interface. Asynchronous Transfer Mode (ATM) is a high-performance, cell-oriented switching and multiplexing technology that utilizes fixed-length packets to carry different types of traffic [9]. Moreover, ATM is connection oriented and allows the network to allocate resources based on the user's needs. This is achieved through the Virtual-Channel and Virtual-Path Connections (VPC and VCC) used for routing and multiplexing of several paths into a logical channel.

The main advantage of ATM over Internet Protocol (IP) is that it allows dynamically allocating required resources on a per-connection basis. Specifically, five classes of services exist with each one having its own QoS parameters. These classes are Constant Bit Rate (CBR), Variable Bit Rate - Real Time (VBR RT), Variable Bit Rate – Non Real Time (VBR NRT), Available Bit Rate (ABR) and Unspecified Bit Rate (UBR). The characteristics of each service class are shown in Table 2.

Characteristic	CBR	VBR RT	VBR NRT	ABR	UBR
Bandwidth guarantee	YES	YES	YES	Optional	NO
Suitable for real-time traffic	YES	YES	NO	NO	NO
Suitable for bursty traffic	NO	NO	YES	YES	YES
Feedback about congestion	NO	NO	NO	YES	NO

Table 2. The ATM service classes characteristics.

An LMDS system encompasses all core and access components of a network therefore, making an ATM approach as the interface very attractive. First, protocol adaptation is not required for connection with other networks like ISPs and PSTNs. Second, LMDS systems must support multimedia traffic creating a need to provide *QoS*

guarantees in some applications. Third, ATM is suitable for broadband networks because switching occurs in hardware resulting in high performance. Finally, ATM offers full management of the network and, therefore, users can select and pay for different qualities of service.

F. SUMMARY

This chapter discussed LMDS, one of the emerging wireless broadband technologies. Several issues were addressed related mainly with network architectures, propagation of millimeter waves, network design and capacity. In addition, a comparison between different technological options was given. The chapter III deals with another emerging technology, FSO, in a similar way.

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III. FREE SPACE OPTICS (FSO)

A. BACKGROUND

Free Space Optics (FSO) is another new technology able to deliver broadband services to the home. Instead of radio waves, FSO uses light pulses to send packetized data over the air. This technology also requires a pair of transceivers mounted on buildings pointing at each other. These devices consist of a laser transmitter and an optical detector providing full-duplex capability, which can be mounted on the rooftops, wall or even windows of buildings.

During the last year, FSO or wireless optical networking, as it sometimes called, is one of the hottest topics in the telecommunication world. Two reasons classify this technology as one of the most promising solutions to the “last mile” problem. The first reason is the present demand for bandwidth from businesses. Not only are T1’s lines not sufficient any more, but also a quick installation is required in days due to competition, which FSO can offer. Second, vendors have made significant advances in their products proving that the technology works. This is driven by the interest of large players in the area. The previous year Nortel and Lucent, two of the biggest optical networking companies, struck deals with small fiberless startups, named AirFiber and TeraBeam respectively. Moreover, Cisco and Corning announced last June an agreement to fund another startup, LightPointe. In addition, Alcatel, the largest seller of LMDS systems worldwide announced, on October 22, 2001, an agreement with AirFiber to offer the industry’s first comprehensive metropolitan area network system based on FSO technology [11]. For its part, AirFiber will install its OptiMesh free-space optical networking equipment and fully support Alcatel's OmniAccess 408 and OmniStack 5024 switches. The network will provide service interfaces, such as voice, T1/E1, Ethernet, transparent local-area network (LAN), and Fast Ethernet.

However, FSO technology like LMDS lacks standardization; therefore, many issues exist and vendors follow different approaches. Two of the largest companies, TeraBeam and AirFiber present a star and mesh topology respectively. Referring to similarities between two companies Dan Hesse, CEO of TeraBeam said, ”It’s interesting

that we are lumped in the same camp all the time. Actually, we do not have that much in common. We use different powered lasers, and our architectures and business models are totally different." This chapter, like the previous one for LMDS systems, aims to address the main issues related with FSO systems by discussing the pros and cons of each approach. These issues are mainly network architecture, propagation, network design and capacity.

B. NETWORK ARCHITECTURES

Several network topologies are possible for FSO networks. Point-To-Point (PTP), star, ring, and mesh are all feasible network architectures for laser communications, which have been proposed by equipment manufacturers. In the following sections, a short explanation of PTP, star and ring topologies is given first since the basic principles are similar with the corresponding topologies in LMDS systems presented in the previous chapters. Second, the mesh topology for FSO systems is described in detail. Finally, a comparison between the above-mentioned topologies is discussed.

1. PTP, Star and Ring Topologies

Point-to-point (PTP) topology is the simplest of the physical layouts of network devices. Point-to-point connections mean that two devices (nodes) have a single path for data to travel between them with nothing breaking up that path. On the other hand, in star connections all devices are connected to a central hub utilizing independent links. Furthermore, the central node is usually a hub or a multiplexer that utilizes repeaters to forward data. Finally, in a ring topology all nodes are connected to one another in the shape of a closed loop, so that each node is connected directly to two other nodes, one on either side of it. Note that all topologies consist of a combination of PTP links. Figure 10 depicts these three different network topologies.

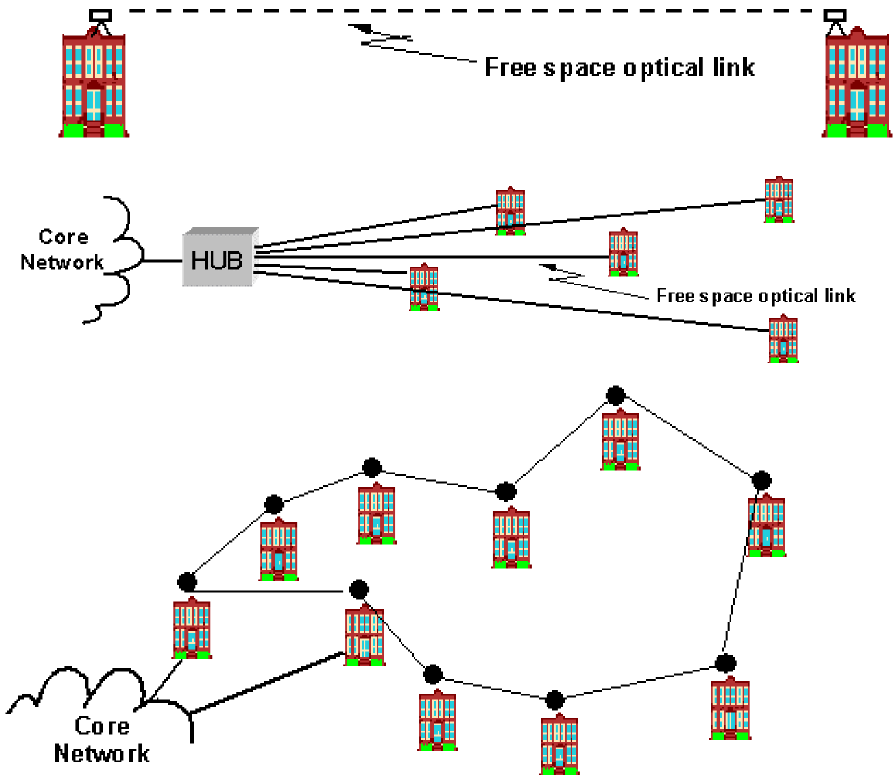

Figure 10. The PTP, star and ring topologies (From Ref. [12]).

Additionally, hybrid topologies including ring, PTP and/or star interconnections have been proposed for FSO systems. In ring interconnections, customer nodes can be ring nodes of more than one ring or one hop away from another ring. At the same time, point-to-point connections with nodes that do not belong to the ring can exist. On the other hand, in star interconnections, central nodes (hubs) are connected with other central nodes utilizing PTP links. The primary reason of extending the standard network topologies is the increase of reliability and coverage area while keeping the associated cost low.

Figure 11 depicts TeraBeam's network architecture that represents a hybrid topology of interconnected hubs. Particularly, each hub serves up to 24 customers in each of its four 90-degree by 90-degree-sectors. Also, hubs are connected via PTP connections.

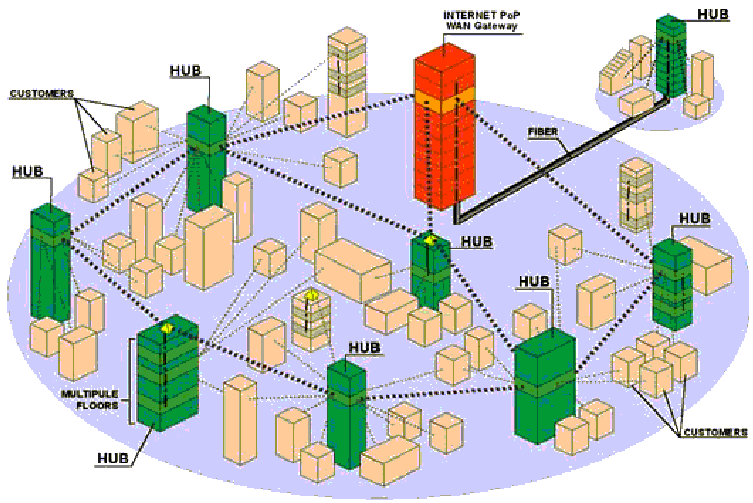

Figure 11. TeraBeam's network architecture (From Ref. [13]).

2. Mesh Topology

In a mesh topology, devices are connected with many redundant interconnections between network nodes. The basic principles of mesh architecture are similar in both FSO and LMDS systems. However, several differences exist specially in the network components. The most representative mesh architecture for FSO systems is the OpticMesh provided by Airfiber [2]. This architecture is discussed in the following paragraph.

AirFiber's OpticMesh is a mesh network configuration of short, redundant links between optical transceivers. Each node is connected with two to four nodes and is able to receive, transmit and forward packets like the wireless nodes in the Radiant's system for LMDS systems. A typical mesh network configuration is shown in Figure 12.

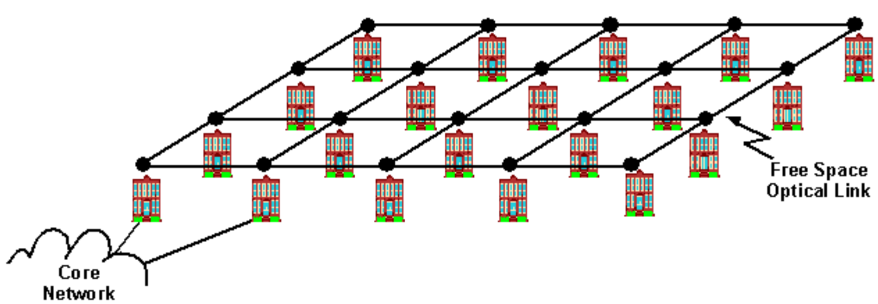

Figure 12. Typical mesh configuration for FSO systems (From Ref. [12]).

The overall network architecture of the OpticMesh network including the core and premise sites is presented in Figure 13. The core sites include the network operation centers in which gateways to carriers/ISPs exist with also switching and routing. Furthermore, the premise site typically includes LAN, PBX and end user devices like computers, telephones etc. On the other hand, the access network is responsible for transforming the traffic from the core network to the premises. The network consists of the FSO equipment, specifically two components: the Roof-Top Systems (RTS) (or nodes) and the Element Management System (EMS).

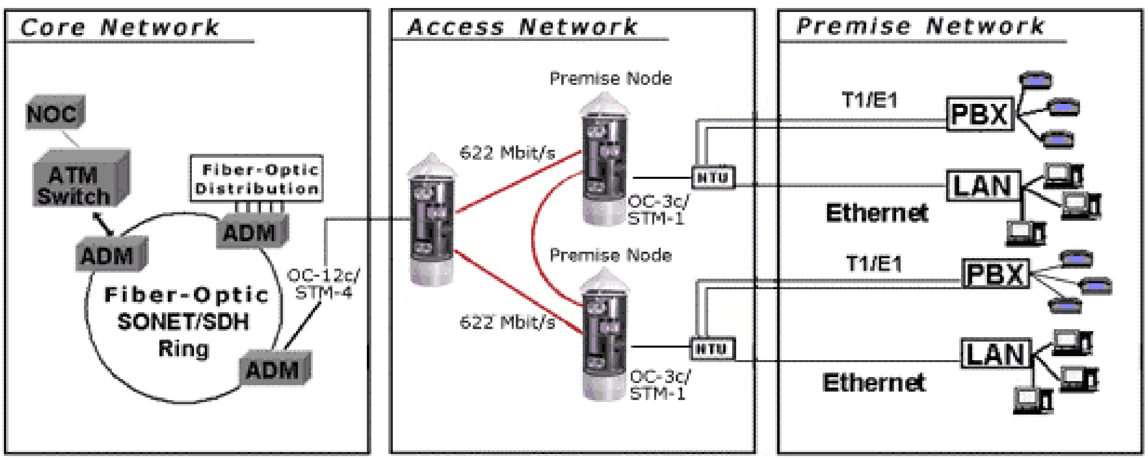

Figure 13. AirFiber's OptiMesh network diagram (From Ref. [12]).

The roof-top systems are the wireless nodes and are typically installed on the tops of buildings in a urban or industrial environment. Each node includes two or four optical transceivers, an ATM switch, a drop to the building demarcation, a control microprocessor and software. The nodes using divergence and active tracing automatically adjust alignment for building sway and thermal expansion. Finally, the connection to the backbone and the customer premises consists of OC3c/STM-1 or OC12c/STM-4 interfaces. Higher capacity is achieved when required by installing more than one node to a building or customer site.

The element management system (EMS) is a graphical easy-to-use, cross platform software package that manages the mesh network and its nodes. Typically, this package is located in the carrier's network operation center (NOC). The functions that can be monitored and controlled from the NOC are configuration, fault management, accounting, performance management and security. The EMS is compatible with Hewlett Packard (HP) Open View and Nortel's Preside Network Management Systems (NMS).

3. Comparison of the Architectures

The choice of network architecture significantly affects the performance, reliability, scalability, design complexity and overall cost of a free space optics network. This section aims to clarify all the above aspects by discussing the trade offs of each approach.

First, in terms of reliability, mesh is the only architecture providing a carrier's grade availability. The high reliability is achieved by utilizing redundant links and nodes that provide intelligent near real-time rerouting to avoid network faults. In contrast, in PTP and star FSO networks, one single link is used per connection, which is a single point of failure. Also, ring topologies are more reliable compared to PTP and star topologies because each node is connected to two other nodes. Consequently, an alternative route is available in case of a link failure.

Network topology scalability is another critical issue for FSO networks. Mesh and ring architectures are considered the most scalable topologies. Network nodes can be added relatively easy as the network grows in order to connect new customers or to provide redundancy. On the other hand, PTP and star systems are not very scalable, as connectivity to a new customer requires LOS with a central location in which a node or hub exists.

The overall cost of a FSO network depends on many factors. Generally speaking, PTP architectures do not have any redundant links or expensive central hub equipment like star topologies and, therefore, are cheaper than the other approaches. However, as the network grows and so does the number of customers, star systems are more economically compared to PTP systems. Furthermore, ring topologies are not very costly for a

sufficient number of customers, so depending on the specific layout of the network it is possible to provide the cheaper solution. In contrast, mesh architectures are the most costly since multiple links are required per building and, therefore, a larger total number of nodes is required.

Moreover, design complexity is different for the network topologies under consideration. Since PTP does not require any complex network architecture or planning due to its simplicity, it utilizes a single link to connect each customer; these links are independent. On the other hand, star systems are more complex because hub locations are chosen in order to maximize the coverage area considering the LOS limitation. In ring and mesh networks, choosing a location for nodes that insert bandwidth is not a difficult task, but managing bandwidth is a significant issue as many problems can arise due to high data rates.

Finally, performance is another important issue affecting the choice of network architecture. The PTP configuration provides the highest bandwidth utilizing dedicated connections. Star topologies can also offer high bandwidth to use independent connections for customers with non-share capacity. In contrary, ring and mesh topologies bandwidth is shared among the users. In ring networks this can especially be a problem while in mesh networks adding more nodes that insert bandwidth to the network can solve the problem. This is achieved by intelligent routing utilizing the multiple redundant links that exist in mesh architectures. Additionally, ring and mesh topologies require a common protocol through the network.

Currently, FSO networks mainly use PTP, mesh and star topologies. For many years PTP laser connections have been used for buildings interconnection in a campus, hence PTP connections are operationally proven. As the cheapest and simplest solution, are supported from all FSO providers. AirFiber also strongly supports mesh architecture mainly because it provides carrier’s grade reliability. On the other hand, TeraBeam and Light Pointe prefer a hybrid network configuration with multiple stars interconnected in a kind of ring topology with PTP links.

In summary, it seems that no standard configuration exists. Equipment vendors try to provide high bandwidth and reliability by keeping the cost low. Consequently,

providing higher reliability typically is more expensive since multiple links are required, the topologies in the near future will be probably mesh, or hybrid (star interconnections) but in a lesser degree. That means in a mesh topology outside of the main network, customers will be served from boundary nodes having probably only one connection and therefore paying less of a fee.

C. PROPAGATION ISSUES

Free space laser communication requires strict LOS operation like LMDS systems. However, FSO systems operate in much higher frequencies than LMDS systems; therefore, different factors affect the attenuation of laser beams when propagating through the air. In this section, an overview of the propagation issues in FSO systems is first given followed by a link budget analysis.

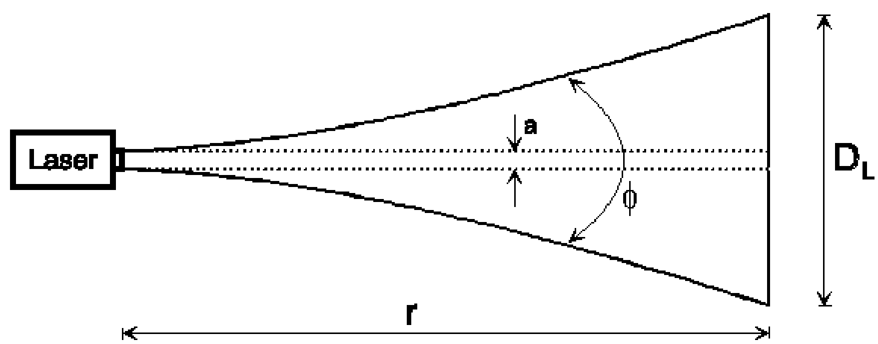

Figure 14. Laser beam geometry in free space.

1. Main Considerations in FSO Systems

The FSO systems consist of laser communication systems. Figure 14 depicts the profile of a Gaussian laser beam that propagates through the air. The beam diameter D_L is a function of the range (r) and given by

$$D_L = \sqrt{a^2 + r^2\phi^2} \qquad (3.1)$$

where α is the beam waist (beam diameter at the exit point) and φ is the beam divergence.

In addition, when laser beams propagate through the atmosphere, their intensity attenuates due to absorption and scattering. The weather condition affecting primarily light waves is fog. Fog is composed of water droplets between a few and a hundred microns in diameter, which allow absorption, scattering and reflection to occur when laser beams pass through fog. For example, thick fog that results in visibility of approximately 150 meters can cause attenuation of 100 dB/km. Furthermore, laser beams are affected by heavy snow and rain that can cause attenuation to the laser beams of 60-1000 dB/km. However, FSO systems in short ranges like 500 m provide link margins for atmospheric attenuation between 30 to 50 dB. Consequently, a system with link margin of 50 dB, even in the case of thick fog, does not have a problem with the atmospheric attenuation.

2. Link Budget Analysis

Beer's law [18], as follow, gives the attenuation of laser radiation through the atmosphere:

$$\tau(R) = \frac{P(R)}{P(0)} = e^{-\gamma R} \qquad (3.1)$$

where τ(R) = transmittance at range R,

P(R) = laser power at R,

P(0) laser power at the source, and

γ = attenuation or total extinction coefficient (per unit length).

Furthermore, a link budget analysis of a FSO system requires knowledge of both the internal parameters of the transmission system and the physical properties of the wireless path. Thus, the above equation is extended to provide the received power, which is finally given by the following equation:

$$\mathrm{P}_r = \frac{P_t \cdot e^{-\gamma R}}{A} L \qquad (3.2)$$

where P_r = power at the receiver,

P_t = transmitted power,

A = the area of the beam at the receiver, and

L = the loss due to scintillation, system optical loss and pointing loss.

The attenuation coefficient is primarily affected by the atmospheric absorption and scattering from different aerosols and molecules. The main factor causing atmospheric absorption is the density of molecules like H_2O and C_2O. The concentration of these molecules varies according to weather conditions and altitude. For some wavelengths, absorption is also very high resulting in significant power loss. However, typical wavelength values of FSO systems are 785 nm, 850 nm and 1500 nm. These wavelengths correspond to atmospheric windows where the attenuation is very small; thus, the absorption attenuation also is very small.

On the other hand, the effects of scattering contribute significantly to the atmospheric attenuation factor. The type of scattering depends on the size of the scattering object with respect to the transmission laser wavelength. When the size of the molecular and dust particles is much smaller than the laser's wavelength, Rayleigh scattering occurs. At the same time, when the scattering object is much larger than the wavelength, selective scattering occurs. The effect of Rayleigh and non-selective scattering on the attenuation coefficient is very small for the wavelengths that lasers operate [19]. Mie scattering, in which particles are comparable in size with the wavelength, primarily affects the attenuation coefficient. Finally, the attenuation coefficient due to Mie scattering is given by

$$\gamma = \frac{3.91}{V} \frac{\lambda}{350} \left(\frac{\lambda}{350} \right)^{-\delta} \qquad (3.4)$$

where V is the visibility in kilometers and λ is the wavelength in nanometers. Visibility technically is defined as the distance that light decreases to 2% of the original power or qualitatively, as the maximum distance in which a dark object is distinguishable against the horizon [22]. Furthermore, δ depends on the visibility: $\delta=0.585(V)^{1/3}$ for V<6 km, δ=1.6 for V>50 km and δ=1.3 for 6 km < V < 50 km. Typical values for the attenuation coefficient in clear air, haze and fog are 0.1 (0.43 dB/km), 1 (4.3 dB/km) and 10 (43 dB/km) respectively [20].

The beam area at the receiver is given by

$$A = \frac{\pi[d^2{}_{\tau} + (a \cdot R)^2]}{4} \qquad (3.5)$$

where dτ is the lens diameter (cm) and α is the dispersion angle (mrad).

Scintillation, the other atmospheric effect, significantly impacts propagation of laser beams. Scintillation is caused by random variations in the index of refraction of the atmosphere. These variations occur when localized temperature differences exist between the ground and the air at low altitudes in which FSO systems operate. The result of scintillation is a distribution of light and dark patches at the receiver. Therefore, the receiver must respond to the intensity variations caused by the patches. The performance degradation depends on the size of the patches, which scales as the square root of wavelength is multiplied by the range. First, when scale sizes are larger than the beam, the beam can be steered out of LOS by a small amount, which is correctable by a tracking system. Second, when scale sizes are smaller than laser beams the beam diameter spreads, but this also does not affect the system performance for short ranges. In contrast, when the scale size is comparable to the laser beam size, large intensity variations can be observed in the receiver. According to measurements by Light Pointe the amplitude of the laser signal can be decreased by 7-10 dB or even further increased [21]. However, using multiple transmitting apertures of sufficient separation and temporary incoherent laser transmissions, the fading can be reduced by 2-4 dB.

Some practical issues are also very notable in FSO systems. The transmitters can be either Light Emission Diodes (LEDs) (single or multiple) typically 1mW, or lasers (single or multiple) typically 10-20 mW on up to 100mW. The detectors can be Positive-Intrinsic-Negative (PIN) diodes with –43 dBm or Advance Photo Diode (APD) with –53 dBm as minimum received power. Undoubtedly, these are typical values and small differences can exist. Finally, Table 3 provides a loss budget example using typical values. The geometrical loss, transmitted power and margin correspond to an Optical Access T1000X pair of transceivers [15].

Parameter	Value	Units
Transmitted power	10	dB
Distance	686	meters
Beam Diameter	1.72	meters
Beam Area	2.31	$(\text{meters})^2$
Geometric Loss	-26.65	dB
Received max power	-16.65	dBm
Received min power	-40	dBm
Margin	23.35	dBm
Pointing loss	-3	dB
Scintillation	-10	dB
Atmospheric attenuation	-10	dB
Received power	-40	dBm

Table 3. Link budget example for FSO systems.

D. SYSTEM COVERAGE AND CAPACITY

1. Design Issues

The design of a FSO system is characterized by simplicity. All proposed network architectures utilize point-to-point links; therefore, no need for multiple access schemes exists. Laser beams are also extremely narrow, so interference from neighboring beams is not a problem in the design of FSO networks. The approximate maximum distance can be calculated using the loss budget analysis developed in the previous section. This distance is mainly dependent on the operating characteristics of the FSO system used and attenuation factors.

Additionally, all commercial FSO systems use on/off keying as modulation scheme. In other words they transmit data based on binary levels. The main reason for using this scheme is its high power efficiency since it has high peak to average ratios. Thus, symbols are separated as much as possible in the signal space and the probability of having errors is reduced.

Finally, when comparing different topologies like star and mesh, the differences are less than those in LMDS systems. Scalability can be a problem in star networks but can be managed relatively easily by adding another hub (star base station) as the network grows. Note that hubs typically are connected using PTP links and, therefore, only a small number of hubs have to be present at the fibre points of presence. On the contrary, mesh architectures are almost the same as those in LMDS systems, so scalability is not a problem. However, in star FSO networks, the location of the hubs can be chosen carefully in order to satisfy the maximum number of customers within the covered area.

2. Capacity of FSO Systems

FSO systems utilize PTP links in all topologies; therefore, bandwidth is allocated per link instead of per area. In addition, the modulation scheme used is on/off keying. As a result, modulation is not a variable that further simplifies the calculation of the total system capacity.

Considering that capacity mainly depends on the data rates that a single link can support, the question in order to estimate the total capacity is "what is the data rate supported by a singe link?" This question is difficult to answer for several reasons. First, supporting data rates are a function of the distance between the transceiver and receiver. Second, as explained in previous sections, local weather conditions significantly affect data rates and transmission distances. Third, FSO systems are continuously refined and improved due to the high interest of large companies in the area. Specifically, during the last year Nortel, Cisco, Lucent, Alcatel and Corning have invested a great amount in small start up FSO companies.

Due to the above reasons for the purposes of understanding the capacity in FSO systems, up to date information from the equipment vendors in this arena is given. First,

in PTP configurations, data rates of 155 Mbps to 10 Gbps can be supported at distances of 2 km to 4 km. Particularly, OrAccess claims that it can deliver 10 Gbps, but this claim is not yet operationally proven. On the other hand, TeraBeam provides 2 Gbps now [23]. Also, AirFiber and Light Pointe provide Gigabit Ethernet speeds in PTP links [12], [21]. The data rates in star topologies are the same with the maximum transmission distance being decreased for the PTP connection at 1 km to 2 km. In contrast, mesh networks utilize relatively short link connections of 200 to 450 meters while the existing AirFiber's network supports data rates among these links of 622 Mbps. From these high data-rate links, customers are feed off lower data rates in line with their needs. Typical values are 20 Mbps to 155 Mbps.

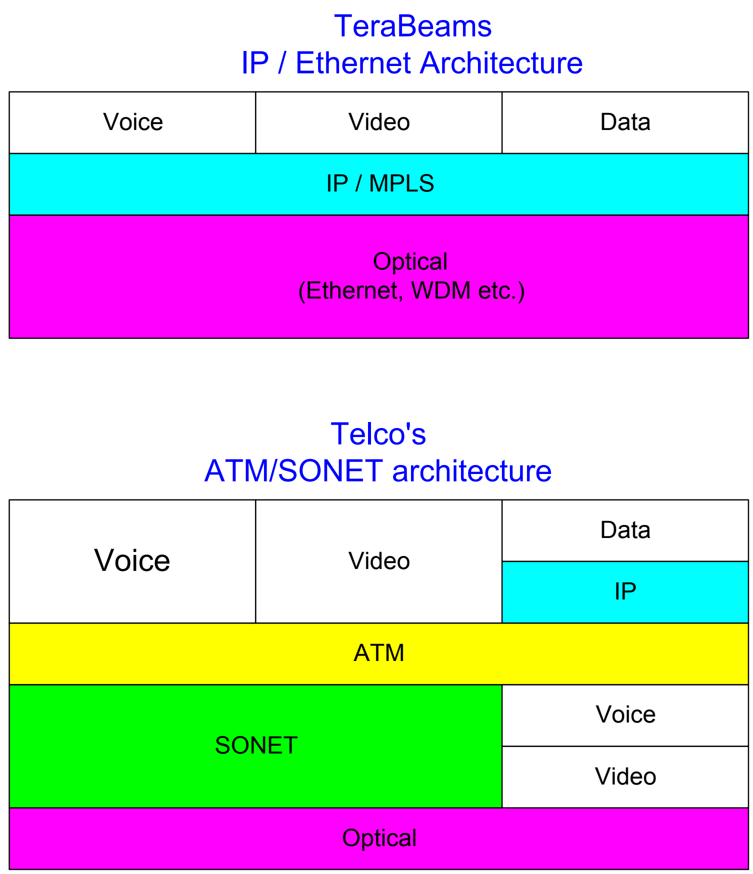

Figure 15. TeraBeam's and Telcos' protocol structure (After Ref. [13]).

E. OTHER ISSUES

1. Networking Issues

Typically, FSO systems are protocol independent since lasers operate as simple repeaters. In this section, a proposal by TeraBeam protocol structure is discussed along with QoS issues.

TeraBeam's network uses IP over Ethernet, a well-known technology, in which no additional protocol transformation is required. In other words, TeraBeam's network connectivity is a type of extension of a company's LAN. Figure 15 depicts both the Telcos' and TeraBeam's protocol structures. This solution allows TeraBeam to offer up to gigabit connectivity achieved by forwarding packets using Multiprotocol Label Switching (MPLS). A four bytes header is examined only at the routers for path determination; thus, less time is required from the router to find the address to the next node and to forward the packet. In addition no fragmentation or reassembly occurs so, the network can support higher data rates. In the near future, the company intends to grow to multiple gigabit data rates utilizing Dense Wave-Division Multiplexing (DWDM) technology.

In the above-described solution Quality of Service (QoS) is also not a problem. The MLPS involves setting up a specific path for a certain flow, identified by a label placed in each packet; this path is appropriate for the needs of each application. Therefore, delay sensitive applications like real-time traffic follow paths with QoS guarantee that is deterministic latency and bandwidth requirements.

Finally, in FSO systems security is also not a problem because the PTP infrared links are extremely secure. Capturing the information requires a receiver that works in the same wavelength as the transmitter. This receiver must be properly aligned near the core of the laser beam and on a solid mounting structure. Since laser beams are very narrow, capture devices must be between the transceivers. This is not feasible because these devices require access to the roof or the room behind the laser.

2. Safety

Another important issue in FSO systems is safety. The major concern comes from expositing the human eye to laser radiation because eyes can be permanently damage from both directed or reflected laser beams. In response to this concern, safety guidelines and regulatory codes have been established for laser systems. Generally, lasers are classified based on the hazard level to a user: the lower the class, the safer the device. According to IEC 60825-1, amendment 2, Class 1 lasers, in which FSO systems must belong, are safe under reasonably foreseeable conditions for operations, including the use of optical instruments for intrabeam viewing.

This classification relies on several parameters, such as laser wavelength, average power over long intervals, beam intensity, and proximity to the laser [25]. Laser wavelength is important because only wavelengths from 400 mm to 1550 mm cause damaged to the retina by intensely penetrating the eyes. Moreover, in order the system to be safe the allowable power level is closely related to the wavelength because the absorption of light by water varies among different wavelengths.

Today's FSO systems operate typically in two areas with respect to their wavelength. This includes short wavelengths of approximately 750 nm and long wavelengths of 1550 nm. The longer wavelengths are absorbed less by the retina than the shorter wavelengths at 750 nm. Although this indicates that at 1550 nm lasers are safer, it is not necessarily true since safety depends on many other parameters.

3. General Issues

Another problem in deployment of FSO systems is that buildings naturally move and sway. This is caused mainly by wind or seismic activity that results in misalignment between the receiver and transmitter and, therefore, in signal interruption or loss. However, two techniques have been developed to solve these problems: beam divergence and active tracking [24]. The key idea behind beam divergence is that systems are designed to allow beam divergence or spreading by formatting a large optical cone from the transmitter to the receiver. Typically, a beam divergence of 3-6 milliards is used

resulting in a beam diameter of 3 to 6 meters per 1 km of distance. Thus by accurately aligning the receiver to the center of the beam during installation, systems can tolerate a sufficient amount of movement or sway of buildings. On the other hand, active tracking utilizes movable mirrors and feedback mechanisms in order for the transceivers to be continuously aligned or as it is usually called "constant footprint." Typically, mirrors are able to move a maximum of 4 degrees resulting in a 70 meter shift both vertically and horizontally at 1 km distance.

In practice, the majority of FSO vendors use beam divergence because it is less expensive than active tracking systems. However, in cases of tall buildings and long distances, beam divergence can be insufficient; therefore, active tracking solutions are a necessity.

An obstruction caused from various flying objects, like birds, is another problem in FSO systems. These objects can block the LOS between a pair of transceivers causing communication to be lost. Although in mesh architectures this is not a problem due to alternative routing, FSO vendors have solved this link breakdown problem. Specifically, when a link is blocked, lasers reduce their power by 10% and when the path is clear again, they transmit in full power for a short time. Therefore, only a slow transmission rate occurs instead of a communication loss [21].

F. SUMMARY

This chapter introduced a relatively new technology, FSO, which is proposed as a solution to the "last mile" problem. The basic concepts were explained and an objective comparison between technological alternatives was discussed. Moreover, a link budget analysis was developed and special issues on these systems like safety were presented. Furthermore, up to date information in this continuously changing area of FSO systems was given, which is one of the objectives of this chapter.

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IV. HIGH ALTUDE LONG ENDURANCE (HALE) SYSTEMS

A. BACKGROUND

The HALO network, which is also called High Altitude Long Endurance (HALE) network, is a new concept for broadband wireless services. However, the technology used in these networks is not new, but are rather components and subsystems from existing proven technology. Thus, the major engineering effort is integration and adaptation. This chapter will provide background information for the HALO networks for purposes of completeness with respect to emerging broadband wireless technologies.

A HALO network consists of an aerial platform that carries telecommunication devices at an altitude of approximately 10 miles. This platform will circle at high altitudes for extended periods of time and will serve as a hub from which broadband communications services will be offered. A single aerial platform can replace a large number of terrestrial base stations, which are well below the Low Earth Orbit (LEO) satellites. Figure 16 illustrates the different wireless broadband solutions and where is the stratospheric communications layer in which aerial platforms fly.

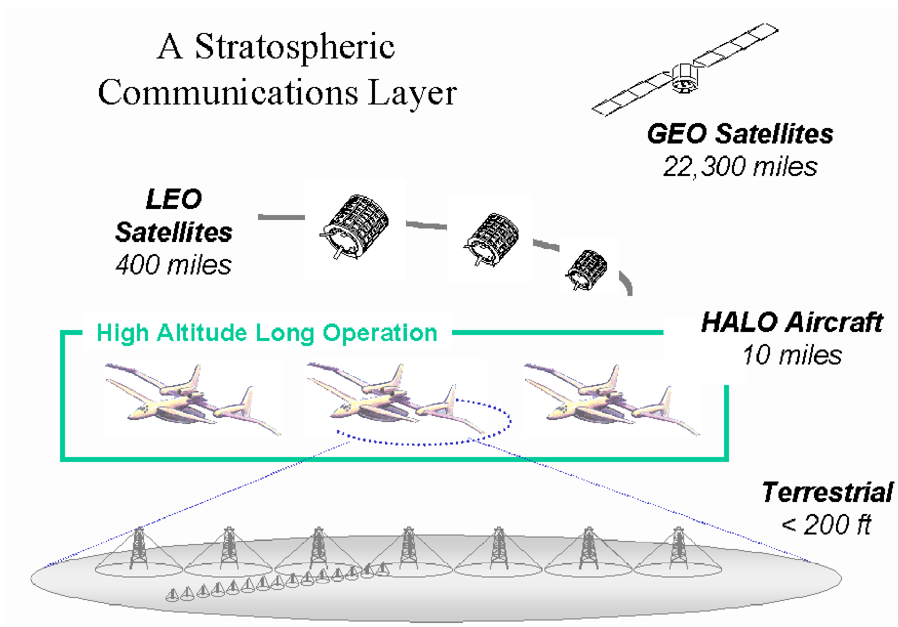

Figure 16. Hierarchy of wireless communication layers ([30]).

B. NETWORK ARCHITECTURES

The HALE networks can be classified into three categories according to the aerial platform used [33]. First, an Unmanned Aerial Vehicle (UAV), which is electrically powered and remote-controlled, can be used. This type of platform uses solar cells or panels and battery power for its electric motors. Helios UAV, which is under development was built by AeroVironment Inc., for NASA. The airplane is estimated to be able to fly and provide service for more than six months non-stop. Second, a balloon can carry the telecommunication relay station. The balloon flies at an altitude between 17 and 22 km because of a layer of mild wind and turbulence. This altitude is above commercial air-traffic heights. Third, an aerial platform can be used as a tethered aerostat. This is an airship on a cable that flights at an altitude of 4-6 km. However, this solution may cause problems to air traffic flys; therefore, it is more suited to aircraft exclusion zones [34].

The most representative HALO network today is the HALO aircraft, which this section discusses; specifically, its architecture and basic components. However, this discussion also covers the other aerial platforms regarding telecommunication concepts, since the basic principles are the same except for the platform being different.

The HALO aircraft is used as a hub of a star topology network connecting users and the outside network. Figure 17 depicts the network architecture of the HALO network. The basic components are as follows: HALO Gateway (HG), HALO aircraft, Customer Premise Equipment (CPE) and Business Premise Equipment (BPE).

The HG connects the HALO network to the core network. Typically, the incoming traffic to HG is ATM. The HALO aircraft has been especially designed to carry the hub of the star network and only one aircraft is required per city. In addition, the CPE corresponds to the terminals of the low-rate users and can support either ATM or IP end users. In the case of IP end users, IP over ATM is used in the terminals. The BPE is similar to the CPE but is a gateway for business requiring higher data rates. All the above components utilize a high-gain antenna that automatically tracks the HALO aircraft. Additionally, these elements differ in size complexity and cost, ranging from the CPE as the simplest to the HG as the most complex [30].

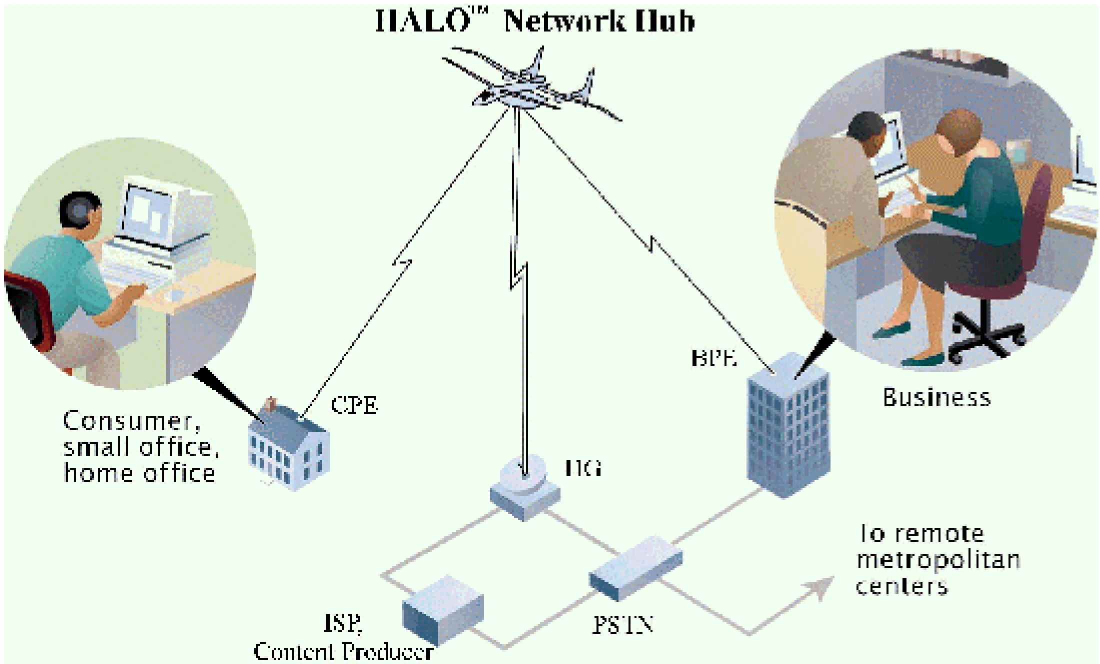

Figure 17. The HALO network architecture (After Ref. [30])

C. SYSTEM COVERAGE AND CAPACITY

A general description of the HALO network design is given in Figure 18. The HALO aircraft will maintain station at an altitude of 23 km by flying in a circle with a diameter of 5-8 nautical miles. According to Angel's plans, three successive shifts on station, each of 8 hours, will provide continuous coverage in a specific area. Additionally, an aerial platform is able to cover an area of approximately 280 square miles. This scenario provides viewing angles higher than 20 degrees and, therefore, high coverage within each area is guaranteed [30].

The network will operate in millimeter frequencies above 20 GHz in a cellular pattern. This is achieved by the airborne hub, which includes an antenna array creating hundreds of contiguous virtual cell on the ground. Typically, more than 1 gateway beam will be utilized based on the required capacity with each cell serving 100 to 1000 subscribers. Furthermore, since the aircraft is above most of the earth's oxygen, links to a satellite can be implemented using the frequencies overlapping the 60 GHz absorption

band for effective immunity from ground-based interference and appropriate isolation from inter-satellite links.

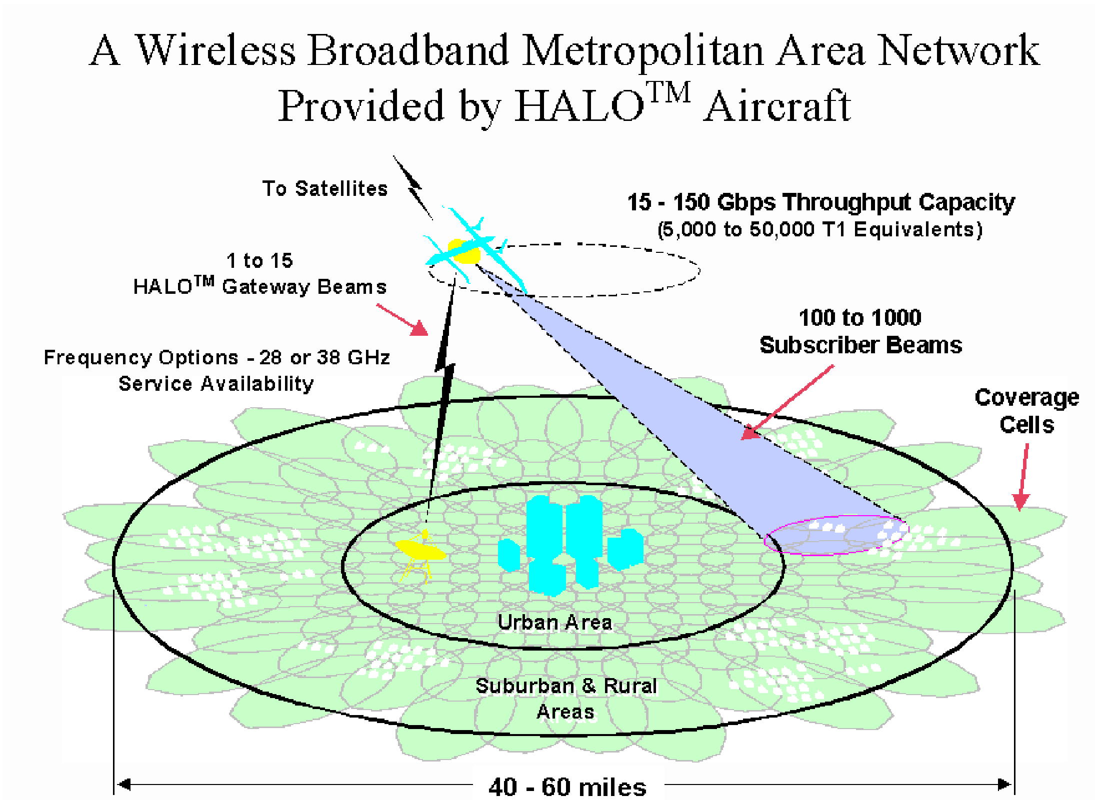

Figure 18. General design of HALO network [30].

There are various classes of service available. A consumer service would provide 1-5 Mbps communication links while a business service would provide 5-12.5 Mbps links. Since the links would be "bandwidth-on-demand," the total available spectrum would be time-shared between the various active sessions. The nominal data rates would be low while the peak rates would expand to a specified level. A gateway service can be provided for "dedicated" links of 25-155 Mbps.

D. SUMMARY

A general description of HALE networks was given in this chapter. Issues of network architecture, design and capacity have been explained based on information provided from two main companies, Angel Technologies and Sky Station, which

anticipate to offer services in the near future. The next chapter discusses a comparison of all broadband access technologies.

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V. OTHER BROADBAND TECHNOLOGIES

In this chapter, other possible broadband technologies are listed and discussed. These other technologies are Digital Subscription Lines (DSL), Integrated Services Digital Network (ISDN), cable modems and satellite access.

A. OVERVIEW OF BROADBAND TECHNOLOGIES

1. Digital Subscription Lines (DSL)

DSL is a broadband technology that uses traditional telephone lines to carry data. Moreover it is an "always on" Internet connection because it utilizes the higher frequencies of the copper phone lines to transmit data digitally. Specifically, DSL modems that are installed at both ends of a phone line, and divide the telephone line into three channels. One channel is used for phone calls, another for downstream traffic and the third for upstream traffic.

There are many varieties of DSL; a common acronym, including all DSL services, is xDSL that stands for data rates above 128 Kbps. Table 4 lists the main forms of xDSL services and their usage. However, connection speeds presented in Table 4 correspond to typical values since data rates in xDSL are highly affected by the distance to the central office (CO) switch. A customer at a distance of 9,500 ft from the CO often achieves a connection speed of approximately 1.5 for downstream while at a distance of 18,000 ft (3.5) only 416 Kbps. Thus, due to distance limitations problems, DSL is only available in metropolitan areas and their surrounding suburbs.

Type	Definition	Characteristics
ADSL	Asymmetric DSL	Provides more bandwidth on downstream than upstream. Primarily used in residential market.
SDSL	Symmetric DSL	Provides same bandwidth on downstream and upstream. Typically used for running servers or other applications that send large amount of data.
IDSL	ASDN DSL	Combines ISDN and DSL providing 144 Kbps.
HDSL	High-speed DSL	Provides equal downstream and upstream from 784 Kbps-2 Mbps.
VDSL	Very High-speed DSL	Provides downstream speed of 13-53 Mbps and upstream of 1.5-2 Mbps. Customers must be 4,500 feet from the central office.
G. Lite	Type of ADSL	Provides downstream speed of 1.5 Mbps and upstream of 384 Kbps. The most common DSL type for residential use.

Table 4. Varieties of DSL services

2. Integrated Services Digital Network (ISDN)

ISDN uses copper phone lines, like DSL, to transmit data. It makes use of twisted pair cables that can carry more information if the problems of cross talk overcoming. This service also requires removal of filters preventing signals of bandwidth greater than 3 kHz being transmitted and an ISDN modem. In addition, the service has three channels. Two channels are called B channels operating at 56 kbps or 64 kbps depending on the configuration from the phone company. A third channel, called D, utilizes 16 kbps and is used for calls. The two B channels can also be connected to double the speed. This type of service is symmetrical offering the same speed for upstream and downstream. Although the maximum data rate is 128 kbps, ISDN is examined as broadband service because it is often the only choice for users providing higher than the simple modem's data rates.

3. Cable Modems - Fibre

This type of service includes a device, the cable modem, giving broadband connection utilizing a cable TV network. There are two types of cable modems: Hybrid Fiber/Coax (HFC) and one-way modem. Both types follow a tree-and-branch architecture as depicted in Figure 19.

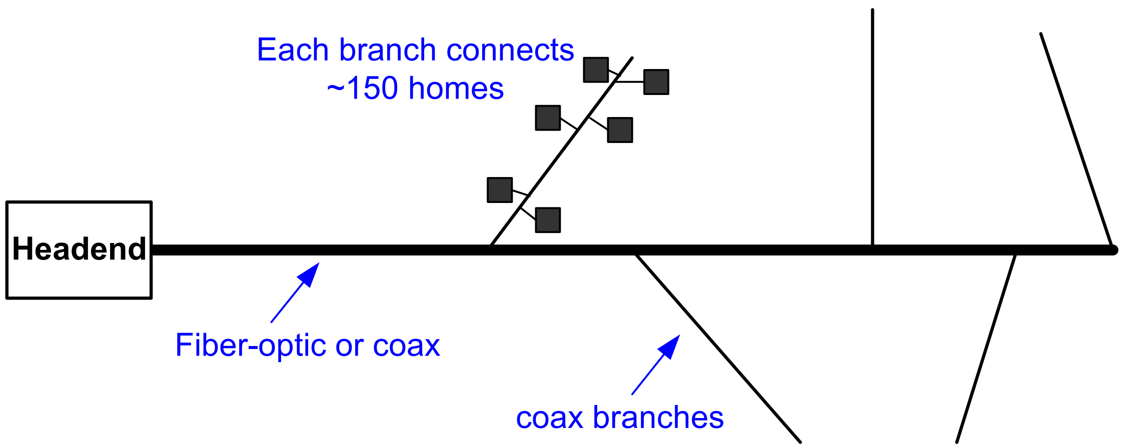

Figure 19. Cable broadband networks architecture.

In the HFC network, known also as Fiber-to-the-Curb (FTTC), a router located at the company's central office and a cable modem located at the customer's site are linked together via a Hybrid Fiber/Coax (HFC) line. The fiber optic is used in the trunk of the tree (backbone network) and the coax is used in the branches. This allows for two-way exchange of data. In contrast, a one-way modem runs over standard cable coaxial networks and offers only a downstream connection of approximately 2 Mbps since these networks were not designed for duplex communications. Thus, this approach requires another Internet connection using a telephone line and a separate modem for sending information.

The most important characteristic of a HFC connection is its operation as a Local Area Network (LAN). Specifically, other users of the same LAN can be neighbors having broadband connection with the same cable company. Therefore, the providing bandwidth is shared among users with no minimum connection speed guarantee existing. Typically,

downstream data rate is from 4 to 8 Mbps and upstream from 200 Kbps to 2 Mbps; however, the company is able to allocate more bandwidth in a specific LAN if the number of customers causes significant performance degradation.

As of late 1999, the total cable lines in the U.S. converted to HFC lines were only 30%. This is due to the high cost of upgrading the old coax lines. Consequently, the other alternative broadband solution, called Fiber-to-the-Home (FTTH), is much more expensive compared to HFC. This technology, FTTH, deploys fiber directly to the customers' premises (instead of coax branches) and it is capable of delivering extremely high data rates of gigabits per second. However, this bandwidth is much more than users require today. Due to its associated cost, FTTH will unlikely to be wide implemented in the next 5 years.

4. Satellite Access

Satellite Internet access allows for high-speed connection via a satellite orbiting the earth. Data travel from a customer's computer to a satellite and then the satellite operating as a repeater forwards the data to an Internet Service Provider (ISP) for further forwarding to the Internet.

Downstream speeds are usually approximately 400 kbps while upstream speed differs and depends on the service provider. Note that older satellite technology does not allow for upstream connections and, therefore, in some cases, depending on the satellite Internet provider, the phone line must be used for upstream connection.

B. COMPARATIVE ANALYSIS OF BROADBAND TECHNOLOGIES

This section provides a comparison among the different broadband technologies. This comparative analysis is divided into three main categories: performance issues, economic issues, and general issues and features. Details for the characteristics in each category are presented in the subsections. The analysis aims to clarify the pros and cons of each technology within the competitive broadband area.

1. Performance Issues

The performance issues compared in the broadband systems are as follow: typical bit rates, reliability and security. These performance metrics have been chosen not only because they significantly affect the system's overall performance but also because they have many differences that occur between different systems.

Typical bit rates for broadband technologies vary. The xDSL data rates significantly vary within the different approaches (presented in Table 4 in a previous section). One of the major disadvantages of this technology, xDSL, is that speed depends on the physical distance from the central office and the copper quality. The further the distance and lower the quality, the slower the average connection speed is. However, a large percentage of population in the U.S. is able to have sufficient bandwidth via xDSL. The largest wired competitor to xDSL, cable modem, typically offers 1.5 Mbps downstream and 500 Kbps upstream on average. Note that this is not a dedicated bandwidth but shared among users and, therefore, no connection speed guarantee exists. Finally, two-way satellite systems offer approximately 400 kbps downstream and up to 256 Kbps upstream while basic ISDN offers up to 128 kbps.

Emerging broadband technologies, LMDS, FSO and HALE, are able to offer greater connection speeds than the traditional discussed solutions above. Of course, data rates differ according to network architecture and design as explained in the previous chapters. However, average connection speeds of 5 Mbps can be offered by LMDS mesh network to more than 200 customers and 1.544 Mbps from a HALE system. Additionally, FSO systems like AirFiber's mesh network claims that it supports 622 Mbps links by feeding customers with 20 to 155 Mbps links according to their needs. Note also that all LMDS PMP and HALE architectures can easily offer much higher bandwidth by allocating more frequency or time slots to a customer and/or by decreasing the cell size in the cellular architectures. Thus, generally speaking, emerging wireless technologies offer larger bandwidth and have greater flexibility in allocating the available capacity of their networks. Furthermore, FSO provides a much larger connection speed than any "last mile" solutions today.

In the above data rate analysis, two things are not discussed. First, HFC networks can offer higher data rates to the customers by decreasing the available capacity for channels or by upgrading the network. However, this upgrade cannot be done easily because of the associated cost. The higher bandwidth requires very expensive cable and lower distances between amplifiers. Second, FTTH is not examined. This solution it is not widely used due to the high installation cost while being almost inactive today. Several trials of fibering homes have been done but the associated cost is still forbidden. Despite the current difficulties, FTTH offers the largest possible transmission rate of 10 to 100 Gbps, so many metropolitan, high density and affluent areas will adopt it after a few years.

Reliability is another important characteristic influencing the performance. Generally xDSL, HFC, FTTH and ISDN systems offer carrier's grade reliability. On the other hand, wireless systems are affected by local weather conditions. Specifically, microwave links are influenced by heavy rain while laser beams are influenced by fog. However, careful planning and designing of the network can result in the carrier's grade reliability. Additionally, reliability is less a problem in wireless meshes architectures since utilizing intelligent traffic management and alternative routes can be found in almost real-time.

Security is the third important characteristic for a system's performance. The xDSL, FTTH, ISDN and FSO systems are very secure networks. The xDSL and ISDN systems utilize phone lines and, therefore, security is the same as for a phone call. Additionally, FSO systems and LMDS mesh architectures utilize very narrow laser beams making it almost impossible to capture the transmitted information as explained in previous chapters. In contrast, the rest of the wireless technologies, PMP LMDS, HALE and satellites are not very secure because the signals are transmitted over a large open space where information is vulnerable to snooping. Finally, security is an issue also in HFC networks. The bandwidth is shared among users; therefore, experienced hackers may be able to break into other computers on the same LAN in the neighborhood. However, cable companies typically take some precautions, so hacking in these LANs is a difficult task.

2. Economic Issues

Broadband technologies are competing in order to provide the same services using the Internet. The economics of the network is critical, because the cost of installation, maintenance and prices will affect the solution to the "last mile" problem. This section examines economic issues in a qualitative way.

The xDSL and ISDN have the lower installation cost because they are based on the existing copper infrastructure of phone lines. In contrast, although HFC is based on the cable network infrastructure, the cost is typically high. The reason is that cable networks have to be upgraded in order to support both broadband connection and cable TV to many customers. Wireless broadband networks also require high installation cost.

Table 5 lists typical equipment costs for broadband technologies. FSO systems are less expensive compare to LMDS systems because they do not require a base station. The approximate cost of a laser transceiver operating in 750-850 GHz is $5,000 while for a transceiver operating at 1500 GHz it is $50,000. Higher frequency lasers offer larger bandwidths and maximum transmission distance. Finally, although satellite and HALE systems require a large initial investment, these systems are not very expensive as they cover a large area allowing the associated cost per customer to be small.

Technology	Equipment cost
ISDN	$50 and up
DSL	$200
Cable modems	$200
One way-satellite	$150
Two way-satellite	$400-500
LMDS	CPE: $1,000-$4,000 Base station: $100 K to $200 K
HALE	CPE: $1,000-$2,000
FSO	Transceiver at 750 GHz: $5,000 Transceiver at 1,500 GHz: $50,000

Table 5. Typical equipment cost for broadband technologies.

Based on the above discussion, xDSL and ISDN are the less costly solutions to the "last mile" problem. The PMP LMDS systems have moderate cost but are more expensive than FSO systems. The HFC have high cost and are more expensive than wireless systems. Satellite and HALE systems require a large initial investment as they are targeted to provide services to a large market share. In addition, HALE is less expensive compared to satellite systems.

3. General Issues and Features

Availability is another significant factor in broadband technologies. Not all technologies are available everywhere as evidenced from the fact that only 2-3 services are offered to customers or to large cities today. The ISDN has the unique characteristic of being provided almost anywhere or where a phone line exists. The xDSL also has expanded availability for customers close to a central office. The service is widespread in medium to large cities, but it is not offered in areas with little demand or incompatible wiring. The HFC is applicable only in certain areas due to the high cost of installation. Moreover, like xDSL, HFC it is not offered in isolated areas. On the other hand, wireless technologies like LMDS and FSO can easily offer services to low-density areas. Today these services are available only in a few large cities but availability continuously grows. Furthermore, satellites and HALE systems generally cover larger areas and, therefore, are suitable for isolated areas. In particular, satellite are offered anywhere in the U.S. requiring a dish that faces south.

Today's business demands call for easy and immediate deployment. Excluding ISDN and xDSL that are based on the existing twisted pair lines, emerging broadband technologies are characterized by fast and easy deployment and installations compared to HFC and satellite systems. Typically, once the network exists, customer premises equipment is installed in one day.

C. SUMMARY

This chapter discussed the competitors to the emerging broadband wireless technologies, which are xDSL, HFC, FTTH, satellite and ISDN. The next chapter develops a deploying strategy for LMDS or FSO systems.

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VI. DEPLOYMENT STRATEGIES

One of the most important characteristics of emerging broadband technologies is the speed and ease of deployment. Careful design is necessary to maximize deployment cost and efficiency of the network. This section provides general guidelines in deploying LMDS or FSO systems. The development of an emerging wireless system consists of three basic parts: the identification of target markets, the development of the business case and the deployment of the network. The following sections discuss each part.

A. IDENTIFICATION OF THE TARGET MARKET

The first step in deploying a broadband wireless system is identifying of the target market. Main factors that must be examined for determining whether an area or country is an opportunity for broadband services are as follows: the current teledensity (the number of telephone lines divided by the population), the Gross Domestic Product (GDP) per head, the competition in the area and the projected growth.

Typically countries or areas with a low teledensity compared to GDP per head present great opportunities for wireless broadband technologies. The number and type of competitors is another significant factor because it affects the price policy. Future growth of the country is also important.

According to studies, there is a connection between teledensity, GDP and growth of a country. Specifically, the International Telecommunication Union (ITU) recommends that teledensity must be at least 20% to foster economic growth or at least to ensure that growth is not hindered by lack of telecommunications [3]. Additionally, countries are typically segmented into three categories: countries with almost no telecommunications (e.g. Africa), countries with low penetration and long-waiting lists (below 40%) and countries with high penetration (above 40%). Statistics and data about the above-discussed issues can be obtained from the ITU. A detailed study and comparison among different countries and areas reveals opportunities in providing emerging broadband wireless services.

C. PLAN OF ACTION

The next step is the development of plan of action. This section offers guidelines in developing the business case. The major elements in the development of a business plan plan be classified into the following: gathering information about the target area, network-building costs, the ongoing costs, revenue predicting and financing.

The required information about the intended area of deploying the network consists of an in-depth analysis of the competition and the market in terms of demand for broadband services. In addition to the data identifying the target market, the development of the business case requires also the penetration of other competing technologies (e.g. cable and DSL) along with current costs. Moreover, the number of businesses and the demand for bandwidth of these businesses is an important factor. The demand for broadband services can be estimated by interviewing potential subscribers.

The network-building costs consist of the subscriber equipment cost and the network equipment cost. The subscriber equipment cost includes the current cost, projected cost, and installation cost. Note that LMDS PMP and FSO star architectures require receivers in the customer's site while in the mesh architectures, the wireless nodes, which operate as receivers, belong to the network equipment cost. One of the difficulties estimating the projected CPE costs is that prices continuously fall as the competition between manufacturers increases. Additionally, due to the high cost per unit, often service providers lease the subscriber units. Furthermore, free installation typically is offered to the customers from the companies. This cost can be calculated considering that four to five subscriber units can be installed per day by a two-person team.

On the other hand, network equipment cost for LMDS PMP and FSO star interconnection networks consists of the base station cost, the interconnection of base stations or hubs, other network elements and operation, maintenance and billing system costs. The mesh architectures instead of having base stations or hubs require the wireless nodes that communicate with other neighbor nodes. The interconnection of LMDS PMP systems can be done by either using microwave links or leased lines. When leased lines are used, a one-time fee is paid but this fee is added to the ongoing cost. In contrast, microwave links are included in the one-time capital cost. The other network elements

may include switches, gateways, servers, network management systems, rental of buildings, redundant power suppliers, redundant interconnection to prevent a single-point of failure and other hardware components.

The ongoing costs include the following: site rental, leased-line costs, maintenance costs, radio spectrum cost (only in LMDS systems), management costs and marketing and sales expenses. Predicting the revenue is a difficult task and usually incurs high errors in the estimations. The associated problems are that customers have to be divided into categories according to their service demand, and the fees have to be consistent with the local competition. Additionally, predicting the number of subscribers over time, bad debts and other potential problems is very difficult. Finally, although in emerging wireless broadband technologies the initial investment is significantly lower compared to wired alternatives like HFC, financing is required. The available options typically are self-funding, direct-funding from banks or financial institutions, vendor financing from the equipment manufacturer and/or shareholder funding. Usually a combination of two or more of these options is chosen.

C. DEPLOYING THE NETWORK

1. Selecting the Technology

The deployment of the network mainly depends on the selected technology. The choice between the two emerging competitive wireless technologies mainly depends on the local weather data in the particular area that the network is intended to implement. Specifically, as it was explained in previous chapters, areas with heavy rains are more suitable for FSO systems while in areas with low visibility (e.g. due to fog) the performance of LMDS systems is affected less. The significance of the influence of weather on emerging wireless technologies is related with the reliability of the system. Considering that business typically requires high reliability, local environment conditions are forbidden many times for the deployment of a system.

2. Selecting Network Architecture

Once the technology has been selected the next important step is the selection of network architecture. The main parameters influencing the selection of the topology are the Wide Area Network (WAN) connectivity and requirements in terms of capacity and coverage in a particular area. The WAN connectivity significantly affects the initial and/or ongoing cost because base stations and nodes inserting traffic into the network must be connected via fiber and/or microwave links. The longer the distance from a Point-of-Presence (POP) the higher the cost. In addition, PMP LMDS systems often required fiber connections in a few base stations and, therefore, the associated cost for the coverage of a specific area is forbidden. In contrast, in mesh architectures, POPs are less a problem because traffic to the network can be inserted using multiple nodes near the POP. Moreover, capacity and coverage depend on the customers' demands that affect the selecting technology and total cost of the network because many vendors exist by offering products differ significantly in prices and performance.

The basic architectures in LMDS systems are PMP and mesh while in FSO systems they are star interconnections and mesh. Since a comparison of the architectures was given in previous sections (Chapter II section B3 and Chapter III section B3) only main points are discussed here. The PMP LMDS architecture is a proven technology while mesh LMDS systems are not operationally proven. Generally speaking, the deployment of LMDS mesh networks is a high-risk investment with problems that can appear related to network management, the steerable antennas and delay. Nevertheless, these networks can significantly improve total capacity and reliability of the network. Comparatively in FSO systems the selection is more difficult since both star interconnections and mesh systems seem to be very attractive and efficient. A general rule is that mesh networks can be implemented in areas in which a high customer density is expected while star interconnections can be implemented in areas where a low density is expected. More explicitly, this factor is related with the predicted link distances and distribution of customers in the network. A mesh network typically provides shorter transmitting distances requiring a close cluster of customers in order to be effective and capable of providing high reliability. The terrain of the area is also very important. For example in generally flat areas without many elevation changes, PMP or star

interconnection systems do not have significant LOS problems and one base station or hub is able to serve a large area. In contrast, when many hills and elevation changes exist typically mesh systems are more efficient since they are able to provide service to a larger number of customers.

Finally, PMP LMDS and star interconnections present similarities in the deployment of the network; mesh LMDS and FSO systems also follow the same steps. Thus, the next sections examine deploying issues of these two groups separately.

3. Deploying PMP LMDS and Star Interconnection FSO Systems

The PMP LMDS and star interconnections FSO systems both require cell sites in terms of areas covered from a base station or hub. Therefore, the design of the network requires the determination of the number of the cells for a particular area. There is a minimum number of cells in order for adequate capacity and coverage within an area to be served. The main factors that influence the required capacity are the number of homes, the density of homes, the expected penetration and the expected traffic per home. The factors determining the coverage area are the size of the area to be covered, the range of the system and the topography of the area. Once these parameters are known, the calculation for the required number of cells is not difficult. For PMP LMDS systems the maximum transmission range is first computed using the formulas given in the link budget analysis (Chapter II section C2) and second, the capacity is calculated as explained in the corresponding part. In the star interconnections FSO systems, the maximum distance and the capacity can also be calculated as explained in previous sections. However, in FSO systems capacity is often not a problem due to the high data rates that are able to transmit; therefore, cell sizes is mainly a matter of the maximum transmission distance. Although cell sizes are affected from many factors, typical values are 3-5 km for PMP LMDS systems and 500-1500 m for star FSO systems while typical distances in mesh architectures are much lower. For example AirFiber's wireless nodes have an average distance of 200 m.

After determining the required number of cells, the location of cell sites has to be selected. Important factors that affect the selection are the LOS limitations and the

backhaul connectivity. The LOS limitations have been explained in previous sections. In order for installation to be more successful, research for potential customers must be done before the installation. Thus, the initial network is able to immediately serve a sufficient number of customers. The interconnection of the cell sites and/or connection to the backbone network depends on several factors: the distance of the link, the required capacity, the presence of available infrastructure, and the availability of radio spectrum. Typically, both PMP LMDS and star interconnection systems utilized a mix of leased fiber links and wireless links.

After making the network operational, the installation of a subscriber's units takes place. In the case of FSO systems this task includes the bolting of the external transceiver on the rooftop or even outside a window. Then, a cable is run outside of the house connecting the transceiver with the CPE inside the house. Additionally, the transceiver has to be aligned to the transceiver at the base station or hub. Furthermore, when LOS is a problem, a solution is mounting the subscriber's unit to a pole erected alongside the building.

The final step is verifying and accepting of the network. This step may include verifying system configuration and end-to-end functionality, demonstrating critical functions of the network (e.g. traffic management) and testing performance. Thus, if all tests are within acceptance levels the network becomes operational.

4. Deploying Mesh LMDS and FSO Systems

On the other hand, mesh architectures do not utilize cells served from base stations or hubs but deploy a sufficient number of wireless nodes in order to provide the require capacity. The deployment of these architectures includes four steps. First, site acquisition and zoning take place. Specifically, in this phase suitable locations for the wireless nodes are determined, acquiring sites on the roofs and obtaining builder-owner permission for installing wireless nodes to roofs. The proposed sites must be able to communicate via LOS at least with two other neighbor nodes; so redundant links increasing the reliability are possible. Additional requirements include accessibility and available utilities. The second step involves site preparation in which the chosen locations

are prepared for the installation of the nodes. Engineering, power and pre-installation (e.g. installing the tripod) issues are addressed. The next step is commissioning. This step includes powering up the equipment, verifying software, and monitoring the proper operation of the network. Finally, system verification and acceptance of the network takes place. This involves verifying and demonstrating the deployed network by examining its performance like in PMP and hub networks. However, mesh networks are complex due to intelligence added to the traffic management and, therefore, verification and acceptance is a difficult task requiring more intense performance tests compared to PMP and hub systems.

D. SUMMARY

Deploying wireless networks is a challenge due to the distinct characteristics of the wireless environment. Thus, efficient design is very important. The purpose of this chapter was to provide and organize simple and practical considerations when deploying such a network. In general all the main aspects of the problem have been categorized into identifiable target markets, developing the business case and deploying the network. Factors affecting each category were discussed and guidelines were given. Finally, this discussion summarized deploying emerging broadband wireless networks. Figure 20 depicts a block diagram of the main steps required. The next chapter deals with concluding remarks for this thesis.

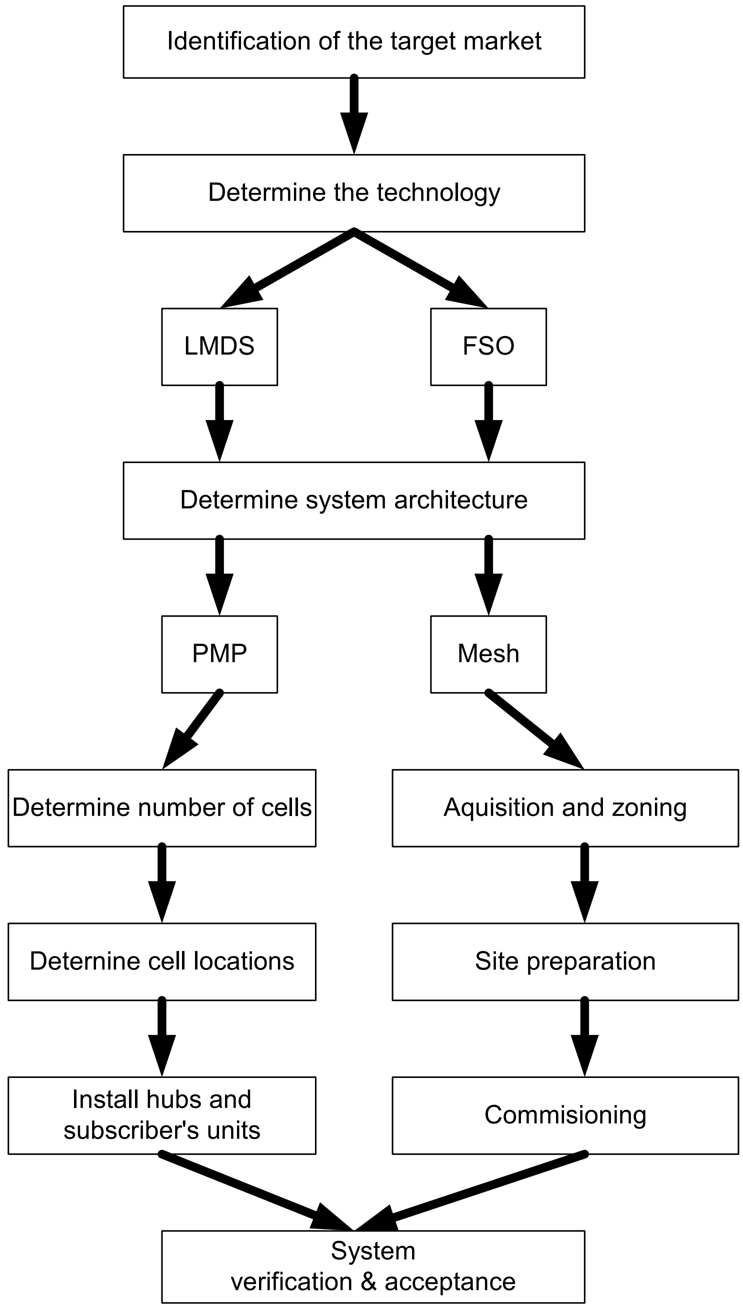

Figure 20. Deploying emerging broadband wireless networks.

VII. CONCLUSIONS

Emerging wireless broadband technologies are among the candidates in solving the ""last mile" problem. Driven by today's demands of larger bandwidth in both business and residential sectors, these technologies are concerned as the one of the hottest topics in the telecommunication's broadband community. However, due to the fact that wireless broadband technologies are in their infancy, no standardization exists. In addition promotional mainly information is available from companies that present advantages of their product. This results often in misleading information and this thesis dealt with an objective assessment in emerging wireless technologies.

In this thesis technological issues related to LMDS and FSO systems were clarified. Additionally, HALE systems were covered for purposes of completeness with respect to emerging wireless broadband technologies. In LMDS systems, mesh architecture promises significant performance and economic benefits compared to PMP architectures. Although mesh microwave networks are expected to gain a significant portion in LMDS systems in the near feature, they have not yet been commercially tested. On the other hand, in FSO systems, the competitive architectures star interconnections and mesh, are expected to co-exist because both have their own benefits compared to the other architectures. Furthermore, PMP LMDS systems are expected to be refined and to implement adaptive modulation techniques in order to increase efficiency. FSO systems in addition are continuously upgraded and capacity is not a problem because generally provide larger data rates than today’s demands.

A comparison among the potential solutions to the "last mile" problem, both wired and wireless was also given. The main benefits of wireless versus wired technologies are ease and fast deployment, lower deployment cost, demand-based buildout and better performance in terms of bandwidth. Although xDSL and cable networks are the dominant technologies in providing broadband services today, emerging wireless broadband technologies expected to significantly increase their market share over the next years. Additionally, FSO systems seems to be a better choice for broadband

services compared to LMDS systems since it is cheaper and more capable of supporting much higher data rates.

Deploying a wireless network is a difficult task requiring more than understanding the technological concepts. This thesis provided guidelines for the deployment of both LMDS and FSO systems by dividing the areas of interest into three categories: identifying the target market, developing the business case and deploying the network. The factors that affect each category were explained, and finally a deployment strategy was provided. This strategy organizes the ideas in a practical point of view and describes in a step-by-step format the major considerations and critical issues in deploying these networks.

An interesting topic of further research is the implementation of the described deployment strategy. For example, a city can be chosen (e.g. Monterey) and all the factors affecting the development of wireless broadband systems can be examined as a case study. This case study could propose a technology for a specific area by discussing the pros and cons of each approach.

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